USAAMRDL-TR-74-59

200

# MANUFACTURING METHODS TECHNOLOGY (MM&T) FOR BALLISTICALLY TOLERANT REPLACEMENT FLIGHT CONTROL COMPONENTS

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Approved for public release;
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Prepared for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
Fort Eustis, Va. 23604

## EUSTIS DIRECTORATE POSITION STATEMENT

This report gives the results of one of three contractual efforts undertaken to develop manufacturing methods for ballistically tolerant flight control components. A previous program by Whittaker on CH-47 components was reported in USAAMRDL TR 73-20. Bell Helicopter Company is currently working on AH-1G components under Contract DAAJ02-73-C-0063. The purpose of these programs is to develop manufacturing methods which will bring down the high cost of R&D items.

In the effort reported here, Whittaker was required to use long fibers or a combination of long and short fiber reinforced materials in the components. Previously, Goodyear Aerospace Corporation had made a UH-1 quadrant completely of short fiber reinforced material; that effort is reported in USAAMRDL TR 73-62.

The manufacturing technology presented in this report is considered to be ready for production items.

This effort was initiated under the technical cognizance of Major Llayll A. Fry and was concluded under Philip J. Haselbauer, both of the Technology Applications Division.

A manufacturing technology data package for these components was prepared under this contract and is available from the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, ATTN: SAVDL-EU-TAS, Fort Eustis, Virginia 23604.

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The objective of this program was to develop manufacturing methods and technology for producing glass reinforced plastic, ballistically tolerant flight control components with a high degree of reliability while utilizing low-cost fabrication techniques. This objective was achieved through development of component designs to obtain simplicity and ease of manufacture. Maximum use was made of commercially available, finished material forms which required a minimum of additional processing. Matched die molding processes were developed

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20. Abstract (continued)

which allowed rapid manufacture of parts to final net dimensions. Assembly techniques were developed which utilized adhesive bonding in precision fixtures and allowed a high degree of reproducibility and reliability of the finished component.

Ten complete sets of components, consisting of a quadrant and a connecting link, were prepared for an extensive verification testing program which included mechanical, environmental, and ballistic impact testing. Material, process, fabrication, and quality control specifications were prepared.

# PREFACE

This final technical report covers the work performed by the Whittaker Research and Development Division, San Diego, California, under Contract DAAJ02-72-C-0115 ("Manufacturing Methods Technology for Ballistic-Tolerant Replacement Flight Control Components") from May 1972 through February 1974. The program was accomplished under the technical direction of Major Llayll A. Fry and Mr. Philip Haselbauer, Structures Division of the Eustis Directorate, USAAMRDL, Fort Eustis, Virginia.

The following Whittaker R&D personnel contributed in the capacities indicated. Mr. R. L. Van Auken was Program Manager during the first phase of the program and was responsible for process development. Mr. Rune Anderson was Program Manager for the remainder of the program and was also responsible for the design refinements and the tool design. Dr. K. R. Berg was responsible for experimental verification. Mr. G. C. Jarman was in charge of component fabrication, and Mr. L. D. Tripp was in charge of in-house testing.

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# INTRODUCTION

The objective of this program was to develop manufacturing methods technology and the capability to produce ballistic-tolerant flight control components using low-cost fabrication techniques and to manufacture these components from glass reinforced composite material. Further objectives were to specify manufacturing processes and quality assurance methods, and to prepare a manufacturing technology data package to assure repeatable production of composite material flight control components with inherent reliability.

The initial phase of the program was made up of several study tasks involving configuration design refinements, manufacturing methods evaluation, materials evaluation, and tooling development. In order to meet the objective of low cost, these four tasks were performed concurrently as information regarding materials and manufacturing methods had direct input to the conceptual component designs and tooling studies.

During the course of these tasks, simplicity in design, availability of materials, and ease of manufacturing were the primary considerations. As a result, it was possible to design each of the two components from standard commercially available materials. Materials were selected that required minimum in-house reprocessing. One very significant contributor to the low cost was the availability of NEMA-grade glass reinforced tubing stock which could be directly incorporated into the component design. The more complex shapes, such as the quadrant disc and the end fittings for the connecting link, were matched-metal-die compression molded from an epoxy bulk molding compound (BMC). A process was also worked out where prepreg fabric could be molded together with the BMC material. The assembly of the details was accomplished in special bonding fixtures.

The second phase of the program dealt with the selection and preparation of quality assurance requirements for the fabrication of the ballistic-tolerant flight control components. Due to the simplicity of design, the availability of stock materials making up the components, and the ability to inspect each detail prior to its installation into an assembly, the quality assurance provisions pertain only to the inspection of incoming materials, process control, and inspection of the final component.

The fabrication phase of the program dealt with the manufacture of ten sets of components to be used for the verification testing program. The developed low-cost manufacturing methods and materials were used to fabricate these components. Manufacturing and process specifications were prepared and cost analyses were made for each component.

A verification test program was conducted at the conclusion of the fabrication phase. The test series included fit and function tests and combined environmental, structural, and ballistic impact tests. The results of these tests established that the performance of each of the components is more than adequate for the operational loads.

# COMPONENT MANUFACTURING DEVELOPMENT

## PROGRAM OBJECTIVES

The vulnerability of present-day metallic flight control systems for Army helicopters to ballistic impact damage from small-arms fire has led to the investigation of materials and designs which are less sensitive to ballistic damage. Typical flight control systems consist of control rods acting through leverage components which determine the pitch of the main rotor and tail rotor blades. The components investigated in this program were a connecting link and a quadrant assembly for the UH-1 helicopter.

A solution to the ballistic sensitivity problem has been found in the development of lightweight flight control components made from fiber glass reinforced nonmetallic composite materials. The initial work on these two components, as performed by North American Aviation/Columbus under contract DAAJ02-69-C-0097* established that the multipath load capability of GRP composite materials in combination with honeycomb sandwich material results in components which continue to function even after ballistic hits from small-arms fire. While the initial components fabricated under the aforementioned contract established a sound materials and design philosophy, the manufacturing costs, weight, and reproducibility were unattractive compared to the metallic counterparts. The objective of this program was, therefore, to provide manufacturing methods technology and the capability of producing replacement ballistic-tolerant flight control components for the UH-1 helicopter, using low-cost fabrication techniques. This involved the establishment of appropriate manufacturing processes, quality assurance methods, and a manufacturing technology data package to assure repeatable production of flight control components with inherent high reliability and quality characteristics.

## PROGRAM APPROACH

### Design Considerations

In order to accomplish the above objectives, it was necessary to coordinate very closely design, materials and manufacturing efforts. Basically, the design considerations were:

1. Ballistic tolerance
2. Structural adequacy
3. Manufacturability
4. Weight

* Ballistically Tolerant Replaceable Aircraft Components, USAAVLABS Technical Report 71-4, U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, April 1971, AD516178L, classified Confidential.

### Material Considerations

The major considerations for the selection of materials were not only their cost per pound, but also how readily these materials could be processed into an end item. The development of specific materials for this application was not part of this program. A minimum of in-house materials processing would be required to meet the low-cost objective. Therefore, materials which were available as commercial stock items were highly desirable.

### Manufacturing Considerations

The manufacturing process was a major developmental portion of this program. The main consideration for the manufacturing process was the utilization of manufacturing techniques requiring a minimum of hand labor for the fabrication of details and the assembly of the final components.

## REVIEW OF PREVIOUS DESIGN

The initial task of this program was to review the North American design analysis and the test program which had been reported under contract DAAJ02-69-C-0097. This report provided the load and load introduction requirements necessary for the redesign and selection of materials to be accomplished later. The report also defined the envelope dimensions of each component and defined the described deficiencies of the previously fabricated components as well. A review of the manufacturing procedures specified in this report revealed extensive use of in-house processing, hand labor, precision machining, and sandwich construction, all of which contributed to high cost.

## MATERIALS EVALUATION AND SELECTION

As previously mentioned, it is not possible to consider materials for a specific application without also considering the design and manufacturing process to be utilized. The materials selected must complement both the design and the manufacturing process if the objectives of low cost, ballistic tolerance, and reproducibility are to be achieved. A major consideration in the selection of materials, which is brought out more fully in the Design Refinement section, involved the complex geometry of parts of the flight control components. Producing complex geometries from continuous fibrous composite materials very often results in excessive labor and costs, and poor reproducibility. The development of semiautomated techniques to fabricate the intricate geometries of the subject components was beyond the scope of this work. As will be seen from discussions in the later paragraphs, many of the semiautomated methods are not applicable to low-cost fabrication of the subject components. On the other hand, prefabricated shapes from composite materials are commercially available from a number of suppliers. Examples of these are the well-known NEMA-grade epoxy glass reinforced stock shapes. These stock items are produced by continuous laminating processes in large quantities, and their cost per pound is substantially lower than similar custom fabricated articles.

The design refinement study showed that tubular shapes made from stock NEMA-grade material conforming to G-11 FR-4 would be a suitable structural material for portions of the two components. There still remained, however, a material to be selected for the fittings of the connecting link and the major details of the quadrant assembly. There were no materials or material forms containing continuous glass filament which could be readily fabricated into the complex geometries of these details. The use of chopped glass molding compounds was considered a very practical approach for these elements. They had been used with complete success on a previous program involving the development and fabrication of components for the CH-47 helicopter. This program, however, was somewhat more restricted in that the use of continuous epoxy glass reinforcement was desired. It was a certainty that this material was going to increase the manufacturing cost somewhat, but would certainly assist in the structural integrity.

In order to keep the manufacturing costs to a minimum, the process development phase yielded a technique whereby the combination of the bulk molding compound and the continuous glass reinforcement could be simultaneously molded. The design refinement task substantiated the structural adequacy of this approach, and it was thereby selected as a strong candidate for maintaining a low fabrication cost. The epoxy glass reinforcement selected was chosen on the basis of its structural adequacy, environmental characteristics, and its compatible cure schedule with the bulk molding compound. Selection of the hybrid molding process was based on the fabricability of the component and its resistance to ballistic impact. Several specimens were molded using the hybrid materials and subjected to ballistic impact to determine if the molding compound and the continuous glass reinforcement were working as a unit or if the two materials were failing independently. The results showed that there was good failure compatibility from a ballistic survivability standpoint and that the hybrid composite would perform satisfactorily.

## MANUFACTURING METHODS STUDIES

The manufacturing studies dealt with methods to fabricate individual component details and methods to assemble these details. The primary considerations in each case were low-cost techniques and a high degree of reproducibility. Details of all components could be fabricated from matched metal molded bulk molding compound (BMC), continuous glass reinforced epoxy prepreg, BMC/epoxy glass prepreg hybrid, and NEMA-grade glass reinforced stock tubing. Since the details which consisted of the NEMA-grade stock materials may require cutting to the proper dimensions and configurations, the emphasis of this study was placed on the development of suitable manufacturing processes for the molded details.

The bulk molding material, as received, has a bulk molding factor of approximately 12:1. While the material is readily moldable in this form, the cavity volume to contain the initial charge must be excessively large to hold the full quantity. A method whereby bulk factor and, in turn, the

volume of the initial charge can be reduced is low temperature preforming. This method consists of compacting the bulk material into pellets or rods at a low temperature and pressure. The developed technique produced preforms with a bulk factor of approximately 3:1 with minimal effect on the flow properties of the material. It was also found to be a more reliable method of charging the tool and controlling the initial charge weight. One exception to this was the fabrication of the upper quadrant disc. Preforming techniques were attempted but resulted in poorly formed details. This particular component requires lateral flow through very thin spaces. Preforms which are too densified could not be forced into the highly intricate areas of the mold. Thus, half of the BMC material was charged to the tool in an as-received free flowing state.

Since this program dealt heavily with the use of continuous glass reinforcement, fabrication methods had to be developed in order to rapidly produce individual details from broadgoods prepreg. Three details of the two components contained continuous glass reinforcement which was processed in-house. These are the fitting ends of the connecting link, the lower quadrant disc, and the upper quadrant disc. The manufacturing method sought for these three components was matched-die compression molding, if possible. The emphasis toward matched-die compression molding of these components was influenced by the need to have precision mating surfaces between these and other details. As will be seen later in the report, the connecting link fittings and the upper quadrant disc contained both continuous glass reinforcement and BMC material. In our initial manufacturing methods studies, the continuous glass reinforcement was precured to its final shape prior to molding in place the BMC material. This proved to be unsatisfactory in that poor adhesion was obtained between the two composite materials. Later attempts investigated cocuring of the continuous glass prepreg and the BMC material. This also proved to be unsatisfactory because the pressure required to densify and fill the cavity with the BMC material caused the continuous glass fabric to distort and displace itself in the tool. The chosen method was the fabrication of a continuous glass preform which is B-staged to a point where under the pressure and temperature conditions it has sufficient flow to permit cohesive bonding between the prepreg and the BMC material. The advancement of the continuous glass prepreg preform is such that little or no distortion occurs under the pressure and temperature conditions used to densify the BMC materials. The developed process worked equally well for the connecting link end fittings and the upper quadrant disc details.

The lower disc detail is wholly continuous epoxy glass prepreg. It has an irregular contour and a stepped thickness. The initial attempts were to fabricate the component on a male tool and form the outer surface with the use of a flexible, formed silicone rubber blanket. The male tool was designed such that the molded silicone rubber blanket also acted as a vacuum bag and imparted pressure on the layup during cure and formed the outer surface detail as well. This method of fabricating the lower quadrant proved unsatisfactory because of the lack of surface detail and the inability of vacuum pressure to achieve the desired laminate thickness.

It was undesirable to use vacuum-plus-autoclave-curing techniques because of the long part turnover time and excessive labor and facilities costs. Therefore, it was decided to make a matched metal mold for compression molding of the lower quadrant. This latter process proved to be an extremely successful method of manufacture once the prepreg ply patterns were designed properly to cover the entire part area. The detail and quality of the lamination were excellent.

The one remaining task to be studied was the assembly of the individual details to the two components. In keeping with the lower cost manufacturing techniques, as well as the part-to-part reproducibility, a method using a combined assembly and cure fixture which would properly align and locate each of the details was selected. A major portion of this task was the design and development of assembly fixtures which would accommodate rapid and accurate assembly and bonding of the components. The fixtures were also used to inspect the parts for dimensional accuracy. The fixtures which were developed are discussed in more detail in the Fabrication section of this report.

## CONFIGURATION REFINEMENT STUDY

Since the objective of this program was to develop a high volume, low-cost manufacturing method for each of the two components, the design refinement study utilized to the fullest the information contained in the North American Aviation report. It was obvious from the standpoint of cost that vacuum bag and autoclave forming individual, continuous glass reinforced details, which was used as the fabrication method for the North American Aviation program, would have to be eliminated. Probably of more importance was the elimination of the machined aluminum honeycomb core that was used in both the connecting link and the quadrant assemblies.

Information obtained from the materials evaluation studies indicated that prepared epoxy/fiber glass tubular stock of the NEMA-grade variety could be used. The connecting link attachment fittings and the upper and lower quadrant discs could be fabricated from bulk molding compound or a hybrid of bulk molding compound and continuous glass reinforcement. Based on these assumptions, preliminary design concepts for each of the components were prepared. These preliminary design concepts are shown in Figures 1 and 2.

As shown in Figure 1, the connecting link assembly consists of two molded end fittings, two NEMA-grade glass epoxy tubes, and four molded BMC standoffs. Essentially no modification was made to the existing North American Aviation design envelope for the connecting link. However, the internal structure of the assembly was quite different in that the machined aluminum honeycomb has been eliminated and replaced by four identical matched-metal-die compression molded BMC standoffs. In order that all the environmental requirements for the connecting link would be met, fire retardant materials were specified.

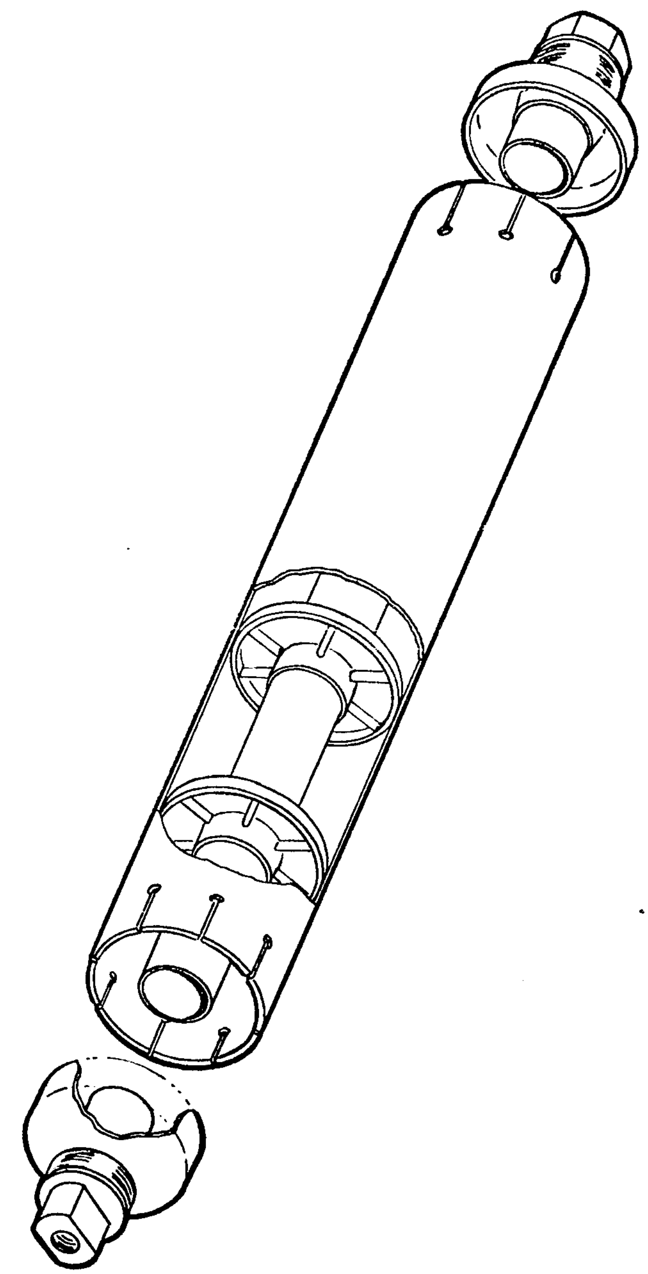


Figure 1. Connecting Link.

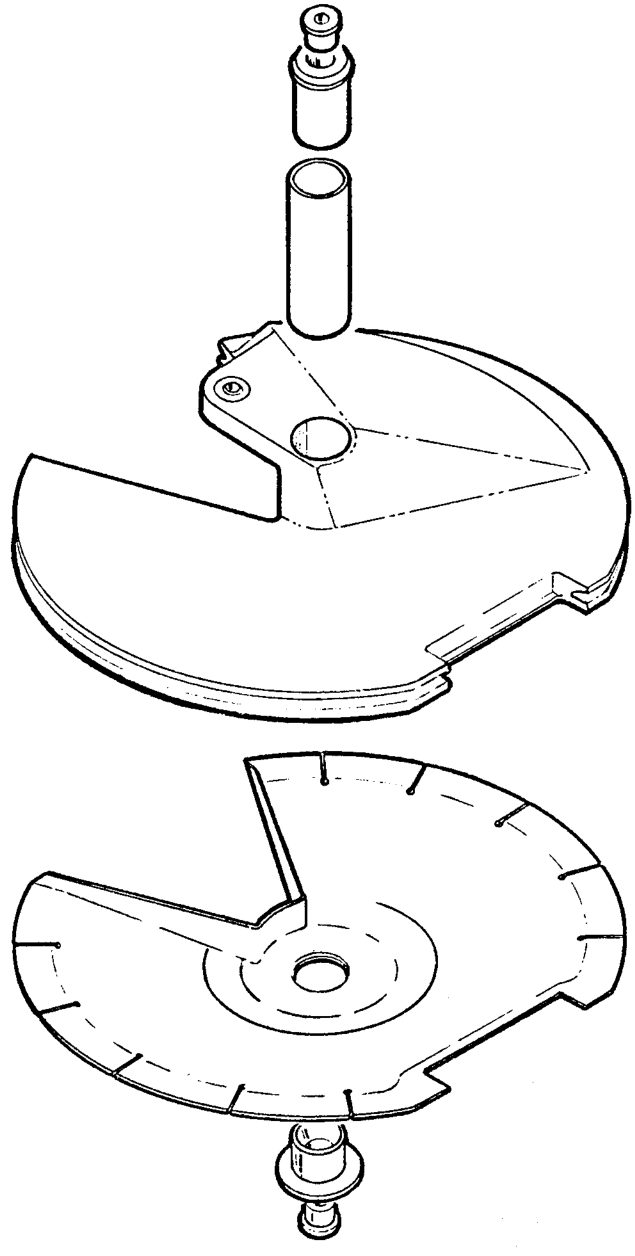


Figure 2. Quadrant.

The quadrant assembly shown in Figure 2 consists of an upper and a lower disc, a NEMA-grade center tube, two BMC inserts, and the necessary metallic bushings and bearings. This design is significantly less complex than the North American Aviation design. The honeycomb core has been removed, the outer contour has been streamlined and reduced in overall volume, and the entire assembly is prepared from considerably fewer details.

In reviewing the design refinement study which was performed on each of the components, it can be readily determined that each has been greatly simplified from a design, materials, and manufacturing standpoint. Having already established the structural capability of each component, a preliminary estimate of the manufacturing costs for each of the components was made to assure that these manufacturing costs had been substantially reduced and made competitive with the metallic counterparts. This analysis was made on the basis of fabricating lots of 100, 500, and 1000 units. Table 1 provides certain assumptions regarding costs which were used to prepare the cost analysis for each component. Tables 2 and 3 detail the specific cost items for the manufacture of each component.

TABLE 1. ASSUMPTIONS FOR COST PROJECTION

| | |
|---|---|
| Based on Quantity of 1000 Units | |
| 80% Learning Curve Used to Adjust Labor | |
| No Learning Curve on Material | |
| Rates Considered: | |
| Laminator/Assembler | \$4.00/hr |
| Inspector | \$4.38/hr |
| Engineer | \$7.00/hr |
| Overhead | 160% |
| G & A | 21% |
| Profit | 10% |

TABLE 2. COST PROJECTION - QUADRANT

Direct Material

| | | | |
|---|---|---|---|
| (1) 1.8 lb BMC | @ $1.90/lb | = | $ 3.42 |
| (2) .7 lb Prepreg | @ $4.00/lb | = | $ 2.80 |
| (3) .4 ft NEMA Tube | @ $3.75/ft | = | $ 1.50 |
| (4) .2 lb Adhesive | @ $4.00/lb | = | $ .80 |
| (5) 2 ea Bearings | @ $2.75/ea | = | $ 5.50 |
| (6) 1 ea Bearing (Ball) | @ $4.41/ea | = | $ 4.41 |
| | Material Cost | | $18.43 |

Labor

Laminator/Assembler

| | | |
|---|---|---|
| (1) | Premold BMC | .3 MH |
| (2) | Cut Layup and Stage Fabric Reinforcement | .5 MH |
| (3) | Mold Upper Disc | .4 MH |
| (4) | Mold 2 Inserts | .4 MH |
| (5) | Cut Tube to Length | .2 MH |
| (6) | Cut and Lay up Fabric for Lower Disc | .6 MH |
| (7) | Mold Lower Disc | .2 MH |
| (8) | Cut Slots and Trim Lower Disc | .3 MH |
| (9) | Assemble and Bond Quadrant | .6 MH |
| (10) | Cure and Clean up | .3 MH |
| | Total Laminator/Assembler | 3.8 MH |

| | |
|---|---|
| Inspector, QC | .2 MH |
| Engineer | .1 MH |

| | Quantity, Units | | |
|---|---|---|---|
| | 100 | 500 | 1000 |
| Labor Cost | $34.40 | $20.98 | $16.78 |
| Labor Overhead | $55.04 | $33.57 | $26.85 |
| Material | $18.43 | $18.43 | $18.43 |
| G & A / Profit | $35.70 | $24.16 | $20.54 |
| Projected Cost | $143.57 | $97.14 | $82.60 |

Cost of Current Production Component - $87.49

## TABLE 3. COST PROJECTION - CONNECTING LINK

**Direct Material**

| | | | |
|---|---|---|---|
| (1) | .4 lb BMC | @ $ 1.90/lb = | $ .76 |
| (2) | .1 lb Prepreg | @ $ 4.00/lb = | $ .40 |
| (3) | 1.7 ft NEMA Tube | @ $ 4.40/ft = | $ 7.48 |
| (4) | 1.7 ft NEMA Tube | @ $ 4.50/ft = | $ 7.65 |
| (5) | .1 lb Adhesive | @ $ 4.00/lb = | $ .40 |
| | | Total | $16.69 |

(6) 2 ea End Fittings
$15.26/ea in lots of 100
$13.22/ea in lots of 500
$ 8.00/ea in lots of 1000

**Labor**

Laminator/Assembler

| | |
|---|---|
| (1) Cut 2 Tubes to Length | .4 MH |
| (2) Cut Prepreg, Form and Stage | .4 MH |
| (3) Mold End Fittings | .4 MH |
| (4) Mold 4 Standoffs | .5 MH |
| (5) Assemble and Bond | .6 MH |
| (6) Cure and Clean up | .2 MH |
| Total Laminator/Assembler | 2.5 MH |
| Inspector, QC | .2 MH |
| Engineer | .1 MH |

| | Quantity, Units | | |
|---|---|---|---|
| | 100 | 500 | 1000 |
| Labor Cost | $23.74 | $14.48 | $11.58 |
| Labor Overhead | $37.98 | $23.17 | $18.53 |
| Material | $47.21 | $43.13 | $32.69 |
| G & A / Profit | $36.06 | $26.74 | $20.79 |
| Projected Cost | $144.99 | $107.52 | $83.59 |

Cost of Current Production Component - $17.39

## MANUFACTURING PLAN

The manufacturing plan for the fabrication of the UH-1 components consisted of three primary stepwise tasks. The first was the molding of each of the component details. The second task was the cutting of the NEMA-grade tubular stock, and the last task was the assembly of each of the details for each component into the assembly fixture and subsequent bonding.

This manufacturing plan was found to be extremely cost effective and highly reliable. The outstanding advantage was the minimum of material processing; that is, the only material which required some in-house reprocessing was the molding of the BMC details and the final bonding assembly. Another specific advantage of this manufacturing plan is the ability to inspect each detail of each component prior to its installation into the final assembly. During the course of the program no components were rejected after final assembly. However, several molded details were found to be not acceptable, specifically the first and second articles fabricated. The use of assembly and bonding fixtures for each of the components was largely responsible for the successful fabrication of each component.

## TOOLING

Tooling developed during the program consisted of matched metal dies for the molding of the epoxy/BMC material and the continuous glass reinforced lower quadrant disc. Other tooling developed was in the form of assembly and bond fixtures and shop aids.

### Matched Metal Dies

Five matched metal dies were designed and fabricated to mold the details for the connecting link and quadrant assemblies. One matched die consisted of an aluminum male tool and a fabricated plastic female tool. The other metal dies were machined from a hardenable steel alloy so that many parts could be molded without deterioration of the tooling. All matched-metal-die tools were designed such that the molded article did not require any secondary processing with the exception of deflashing.

For the work performed on this program, the tools were adequate. The details molded in each of the cavities were of excellent dimensional and physical quality. However, operational difficulty was incurred on the upper quadrant tool, which was a large, massive, and highly contoured assembly. The primary difficulty was associated with the entry of the four main guide pins into the lower half of the tool. Normal practice was to mate the upper and lower tool half while the tool was in the room temperature condition. Both halves were then allowed to heat while together. The heating gradient from top to bottom of the tool was approximately 50 degrees. Since galling was initiated primarily on the opening stroke, it is reasoned that the upper portions of the lower tool half were

cooler than the guide pins which extended down to the primary heating surface. Thus, interference was caused between the guide pin and bushing during opening. The problem was finally resolved by increasing the clearance between the bushing and the guide pin to permit such heat gradients and still make the tool operational. Once this had been accomplished, details were readily molded. The complex configuration of the mold for the quadrant upper disc is shown in Figures 3 and 4.

### Assembly Fixtures

Fixtures were made for the assembly and bonding of the two components. The fixtures held the individual details in their proper positions and provided the necessary clamping pressure for bonding the parts together. Assembly fixtures for the quadrant and the connecting link are shown in Figures 5 and 6.

## FABRICATION OF COMPONENTS

### Connecting Link Assembly

The connecting link assembly was made from two composite materials. The two tubular elements were made from stock NEMA-grade glass reinforced tubing. The end fittings and the standoffs were compression molded in matched metal dies. The fittings are a hybrid molding of continuous glass reinforcement and BMC material, whereas the standoffs are molded of the BMC material only. The connecting link details are shown in the exploded view of Figure 1.

The end fittings were fabricated by molding the BMC material, the continuous glass preform, and the metal attachment insert in one molding operation. First,the continuous glass reinforced insert was prepared by die cutting three patterns of glass/epoxy prepreg. These plies were then formed around a Teflon mandrel and inserted inside a Teflon female tool for staging and forming at temperatures of approximately 150°F for 45 minutes (see Figures 7 and 8). The preforms were then removed from the forming tools and placed in the compression molding tool along with the metal attachment insert. Following the insertion of these two details into the preheated tool, the BMC charge is added as bulk material. This is shown in Figure 9. The assembly is then molded and cured. Two fitting details are required for each connecting link, each having a different attachment fitting configuration. The molded fitting detail is shown in Figure 10.

The two NEMA-grade tubes are obtained as stock material and require only the following additional processing. The inside surface at the ends of the small-diameter inner tube is machined for proper mating to the conical shape of the end fittings. The large-diameter outside tube requires slotting of the ends to enhance ballistic tolerance and to permit pressure to be applied during the bonding process.

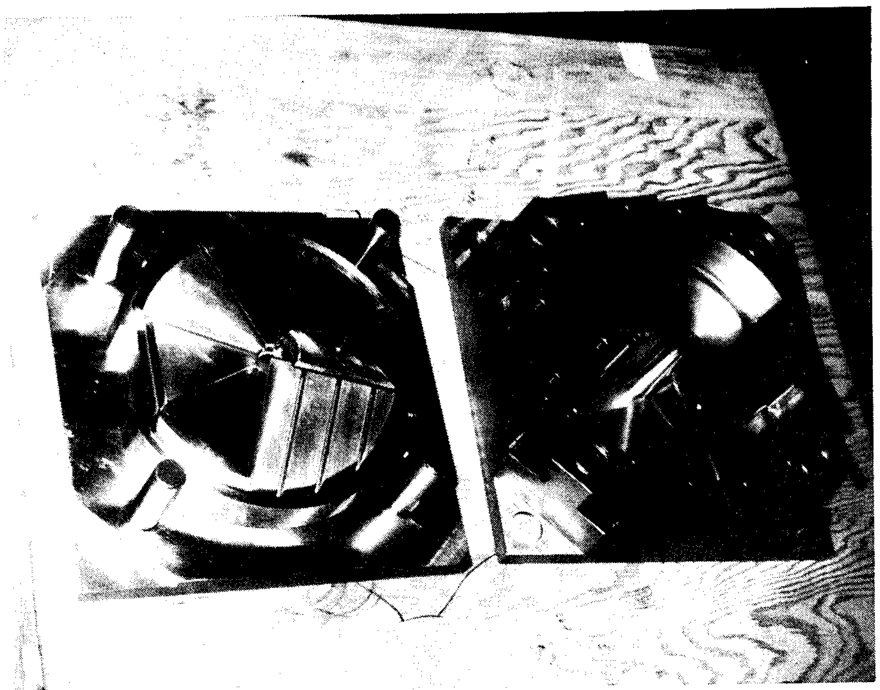


Figure 3. Compression Mold for Quadrant Upper Disc.

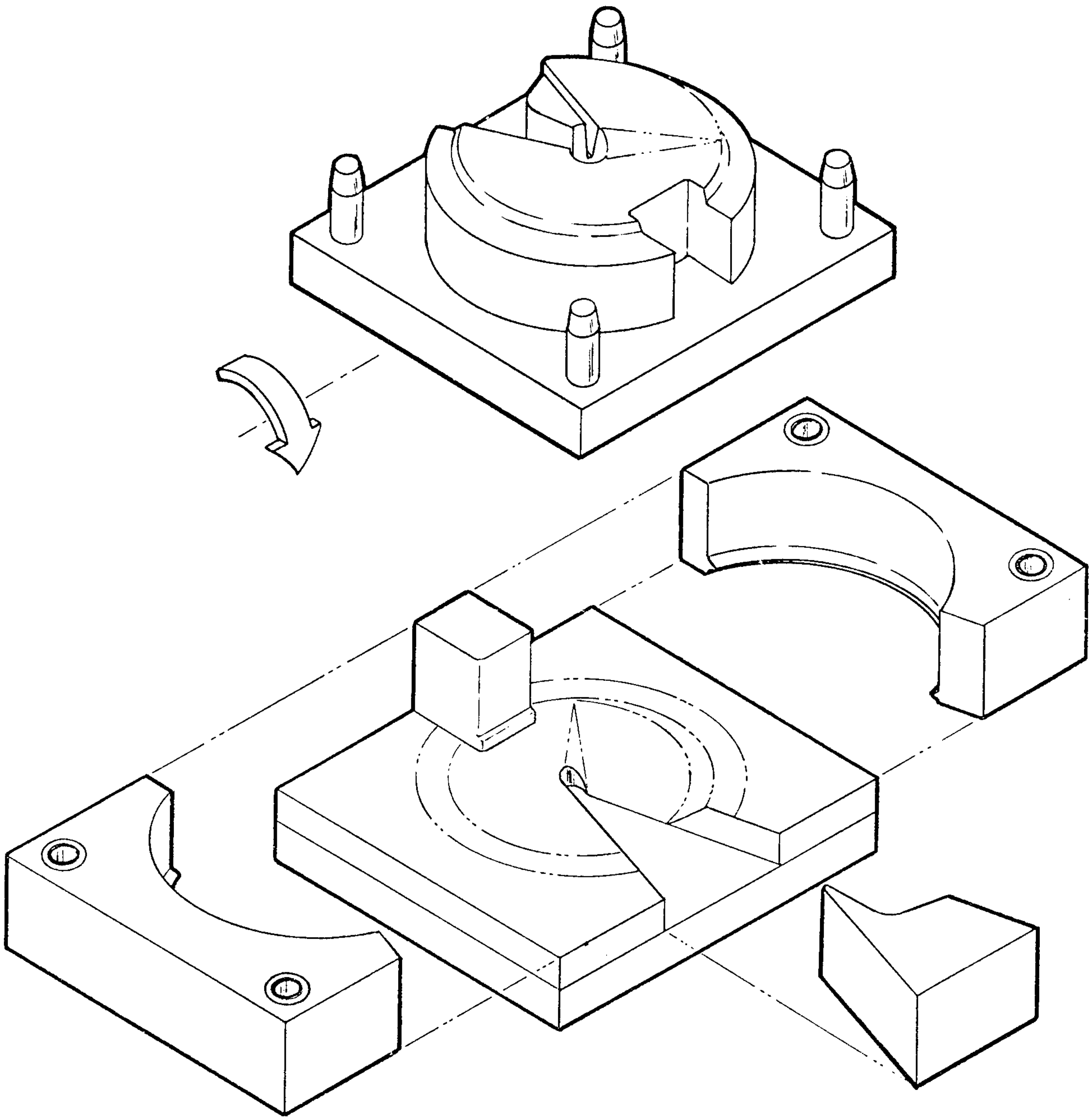


Figure 4. Quadrant Upper Disc Mold Concept.

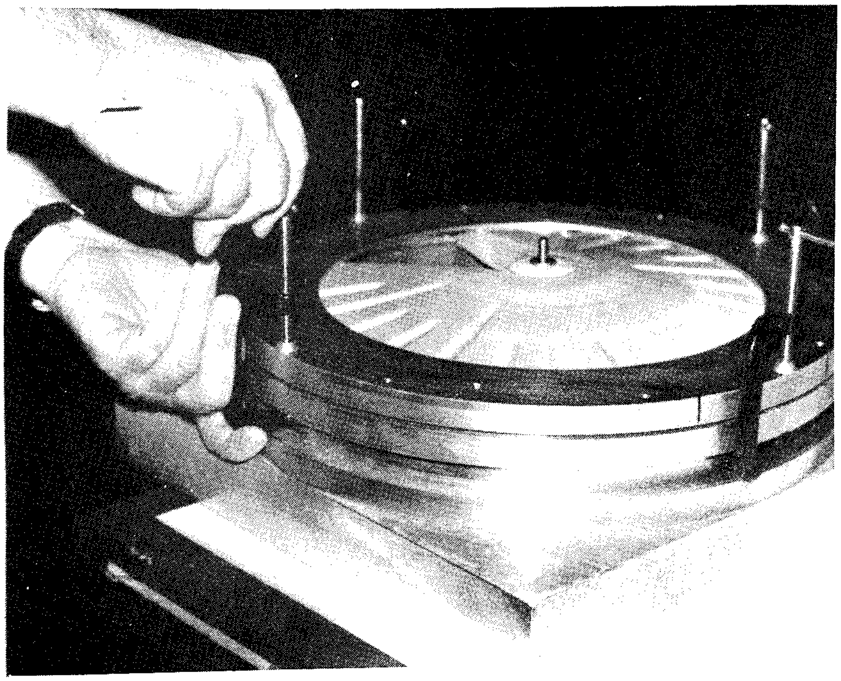


Figure 5. Assembly Fixture for Quadrant.

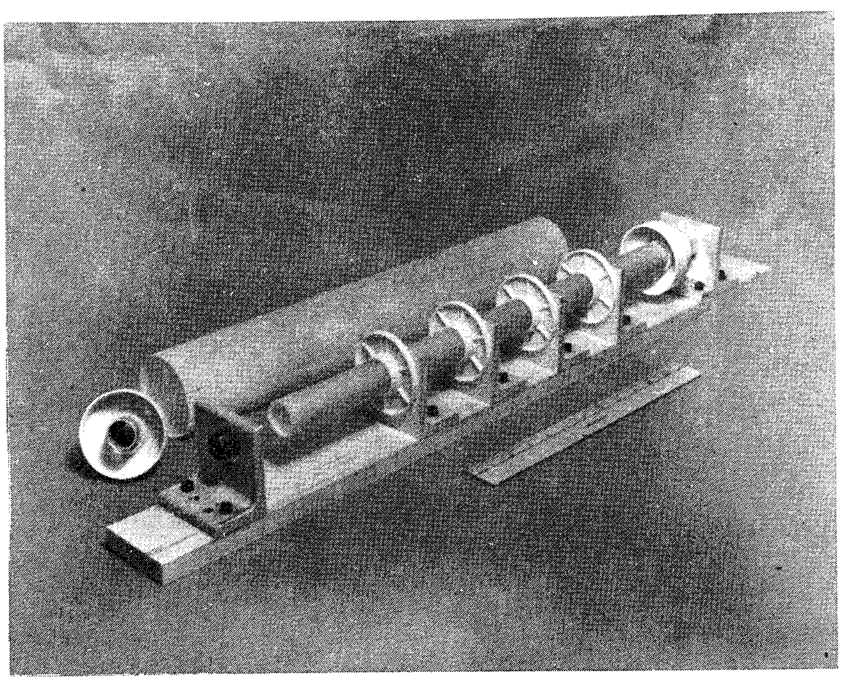


Figure 6. Assembly Fixture for Connecting Link.

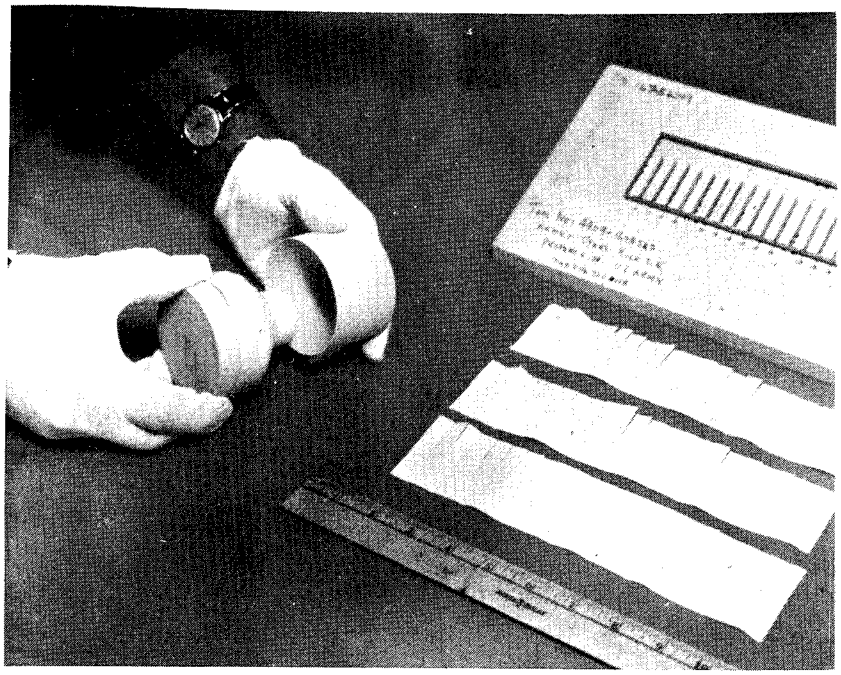


Figure 7. Fabric Pattern for End Fitting.

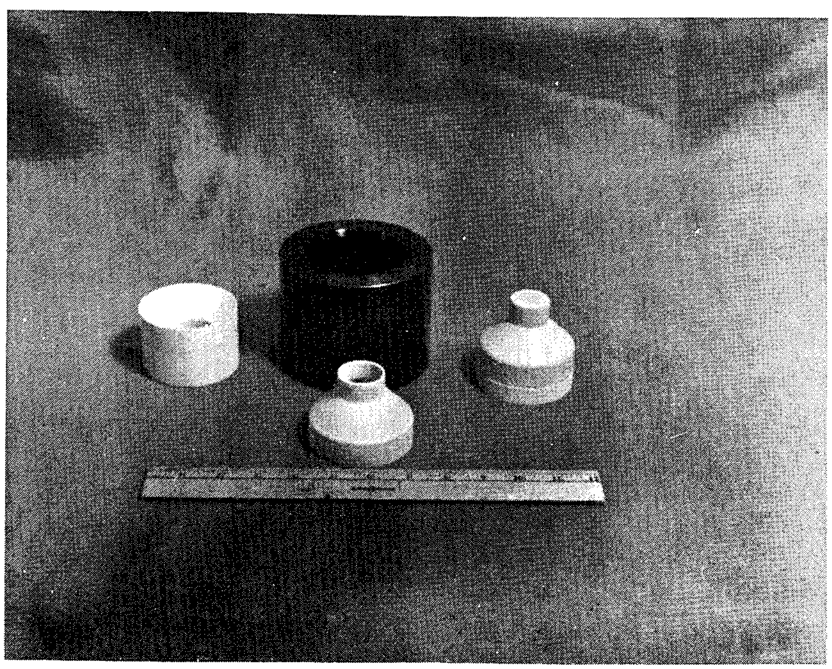


Figure 8. Tool for Staging End Fitting Prepreg.

Figure 9. Mold for End Fitting.

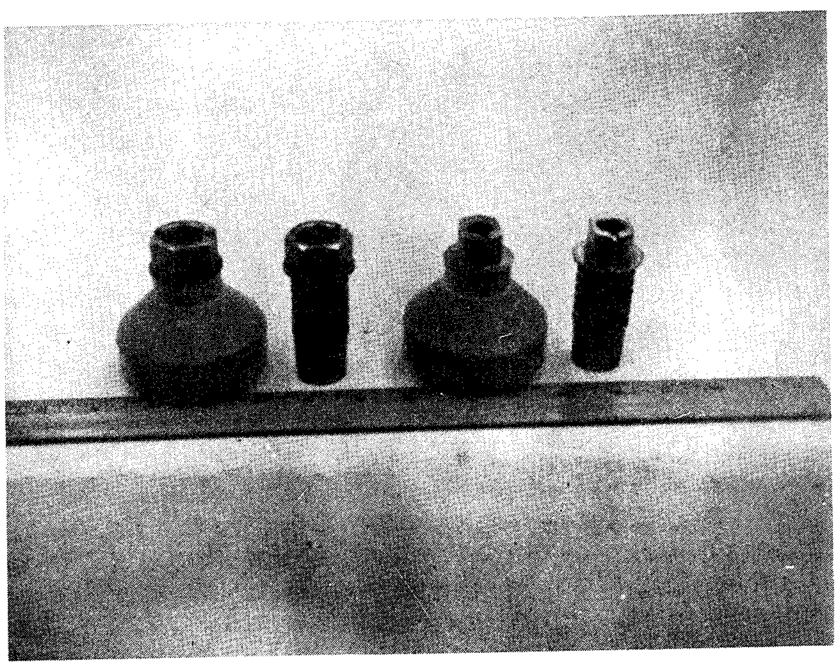


Figure 10. Completed End Fittings for Connecting Link.

The four identical standoffs which support the inner tube are compression molded of BMC in matched metal dies. Holes are drilled through the web in the standoff to allow venting of the airspace and drainage of moisture caused by condensation. The molded standoff and the compression mold are shown in Figure 11.

The assembly of the connecting link is accomplished in two steps. First, using the assembly fixture, the molded standoffs are positioned and bonded to the inner NEMA-grade tube, Figure 6. After the adhesive has cured, the outer tube is slid over the standoffs and the end fittings are bonded to both the inner and the outer tubes. No adhesive is applied between the standoffs and the outer tube. During this operation continuous glass reinforcement is overwrapped at the small diameter of the end fittings to enhance the structural performance. Shrink tape, wrapped around the slotted ends of the outer tube, applies pressure to the bond between the tube and the end fittings. The tape is removed when the adhesive has cured.

Figure 12 shows the connecting link in the assembly fixture, and Figure 13 shows a completed connecting link.

Quadrant Assembly

The quadrant assembly consists of an upper and a lower disc, a short NEMA-grade glass/epoxy tube, two molded inserts, two metallic bushings, and one lug bearing. The quadrant assembly details are shown in the exploded view of Figure 2.

The lower quadrant disc, shown in Figure 14, is fabricated as a separate detail and is made up of several plies of continuous glass fabric epoxy prepreg. The fabric prepreg is cut to size and laid up over a male tool which is then inserted in a matching female die for curing. The use of matched metal dies is necessary to properly form the bead pattern in the disc. After curing in the tool, the disc is trimmed to its final configuration. To simplify this operation, the trim line is scribed on the tool and is embossed in the part during the curing operation.

The upper quadrant disc is compression molded in a matched metal die. The outer face, consisting of three plies of continuous glass fabric epoxy prepreg, and the bulk molding compound which makes up the backup structure are molded in one operation. The glass fabric prepreg is laid up over a Teflon-coated mold, which is made of BMC material, and vacuum bagged. It is then staged at approximately 250°F for 1 hour and 30 minutes. The staging gives the fabric enough rigidity to remain in its proper place in the mold during the subsequent molding operation. The fabric layup and staging are shown in Figures 15 and 16.

For the molding operation, the staged fabric is first inserted in the female cavity of the heated compression mold. The BMC material is then distributed over the fabric in a predetermined pattern. To simplify the

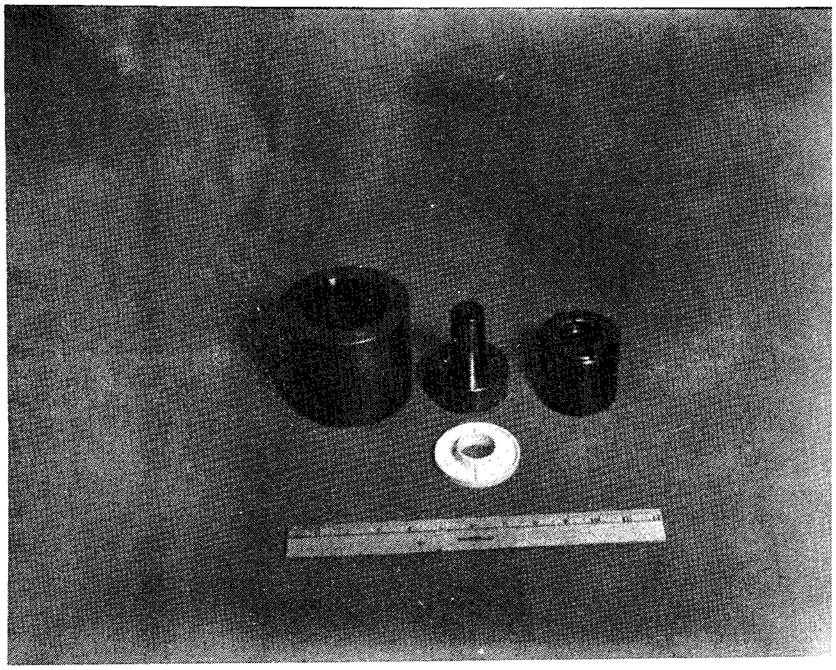


Figure 11. Mold for Standoff.

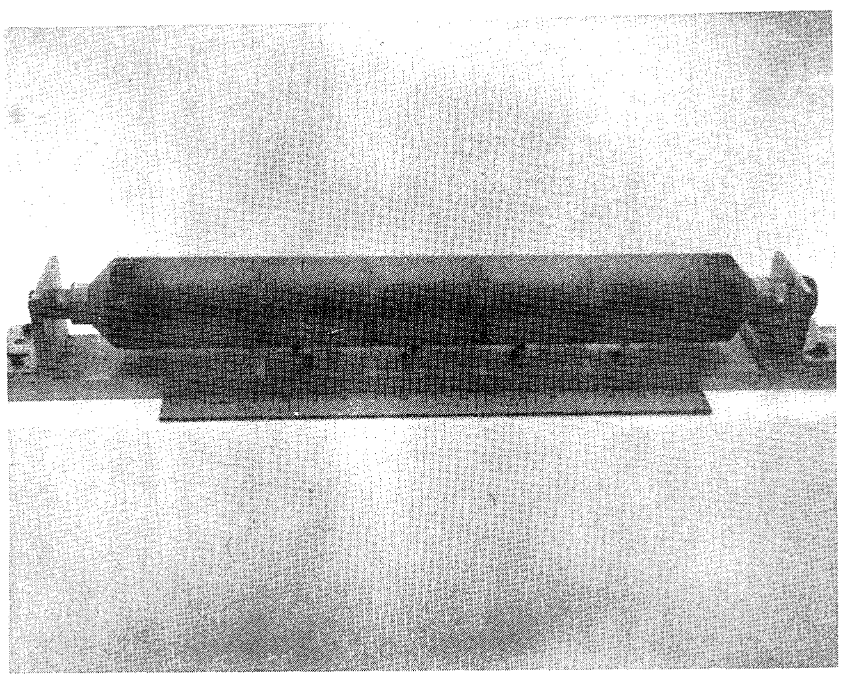


Figure 12. Connecting Link in Assembly Fixture.

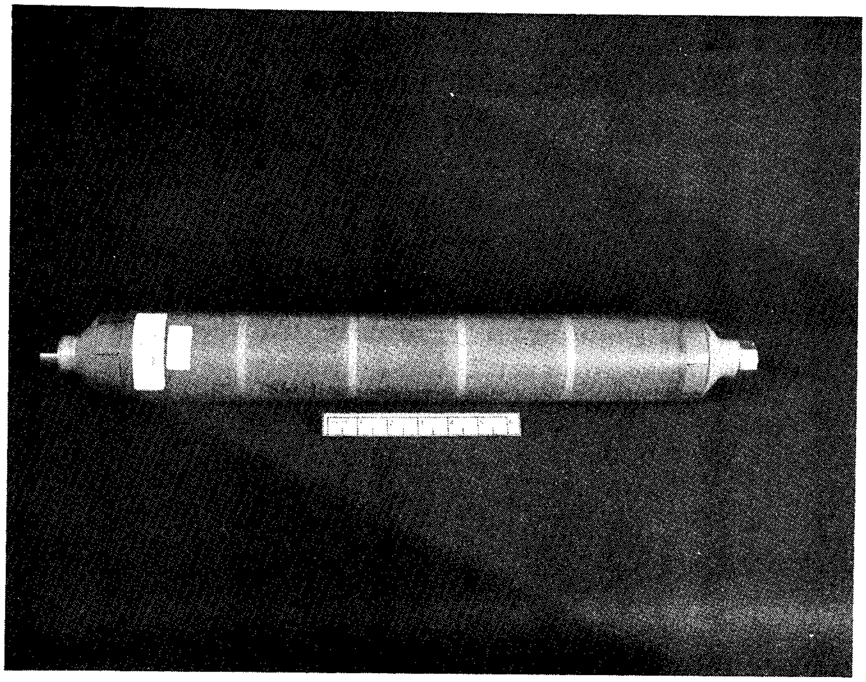


Figure 13. Connecting Link Assembly.

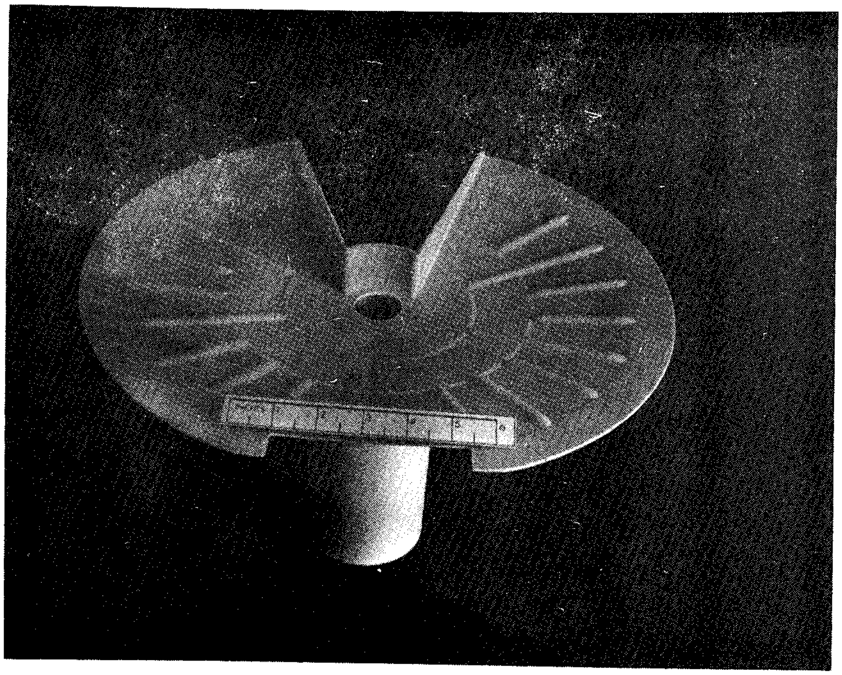


Figure 14. Lower Disc, Quadrant.

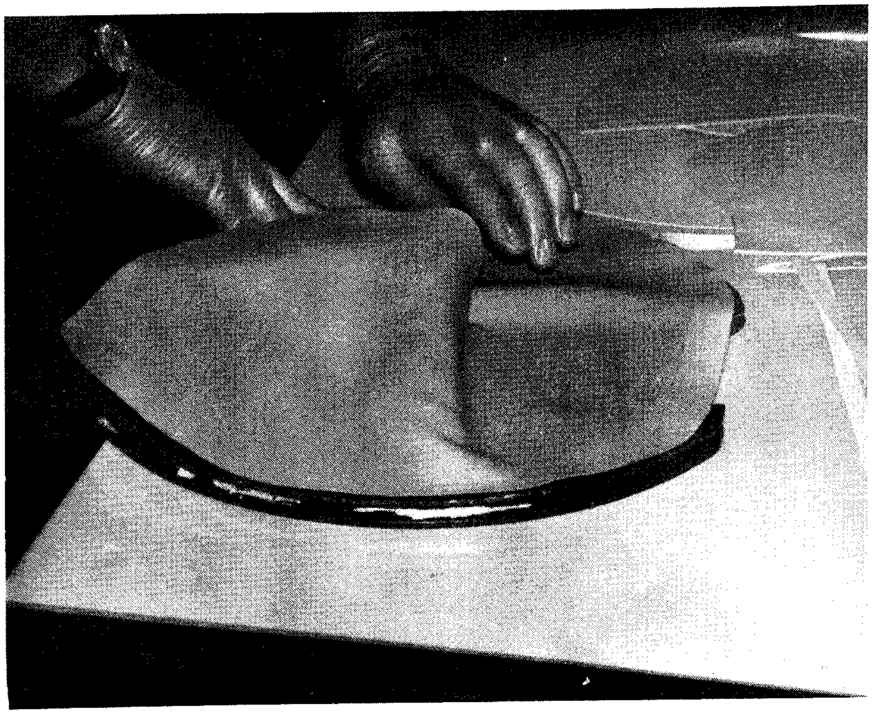


Figure 15. Layup of Fabric for Quadrant.

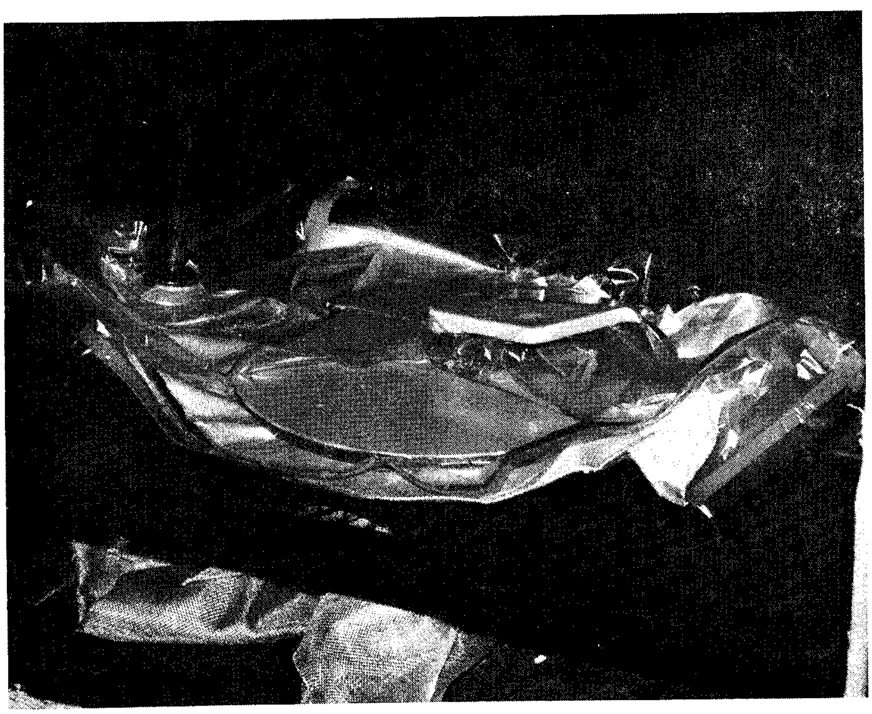


Figure 16. Vacuum Bagging for Staging Fabric.

loading of the mold, the BMC charge is in both bulk form and in precompacted slabs. The molding sequence of the upper disc is shown in Figures 17, 18, and 19.

The two inserts which support the steel bushings are compression molded of BMC in matched metal dies, Figure 20. Together with a short tube made of NEMA-grade FR-4 glass/epoxy, they form the hub and pivoting axis of the quadrant. Longitudinal slots cut in the center portion of the tube make it possible to expand the tube diameter after it is inserted and bonded in the hole in the molded upper quadrant disc, thereby applying pressure on the adhesive during curing.

The quadrant is assembled and bonded in an assembly fixture. The fixture is constructed so that the correct positions of all parts are maintained until the adhesive has cured. All parts, including the metallic bearing and bushings, are bonded in place with EA 9320 adhesive, which is a two-part, room-temperature curing adhesive. Highlights of the assembly operation of the quadrant are shown in Figures 21 through 24. After bonding, removing excess adhesive and flash and drilling two holes for the cable retaining pins are the only operations remaining. Figure 25 shows an assembled quadrant.

### Modified Quadrant Assembly

As discussed in the Test section, the quadrant did not fit properly when installed in the helicopter. The bolts in the lower bearing mount were rubbing against the center portion of the lower quadrant disc. To alleviate this problem, the center tube containing the metallic bearing bushings was positioned 0.055 inch lower in the molded upper disc. A 0.055-inch-thick washer made of NEMA-grade FR-4 epoxy/glass fiber laminate was placed between the flange of the lower molded insert and the lower disc. This arrangement had the effect of raising the disc portion of the quadrant 0.055 inch with respect to the lower bearing. The modification to the quadrant is shown in Figure 26.

## VERIFICATION TESTING

The testing conducted during the course of this program was comprised of three separate tasks. The first was the fit and function test, the second a series of combined mechanical and environmental tests, and the third a ballistic impact test. Ten quadrants and eleven connecting links were fabricated for this test series. Table 4 details the test series and sequence for each of the individual components. It should be noted that one set consists of one each of the two different components.

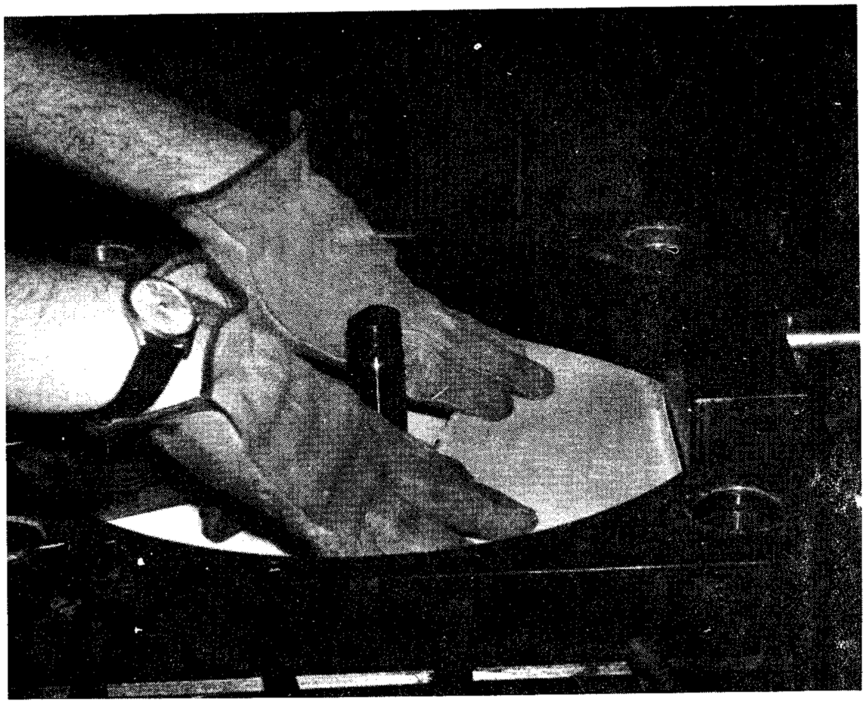


Figure 17. Inserting Staged Fabric Disc in Mold.

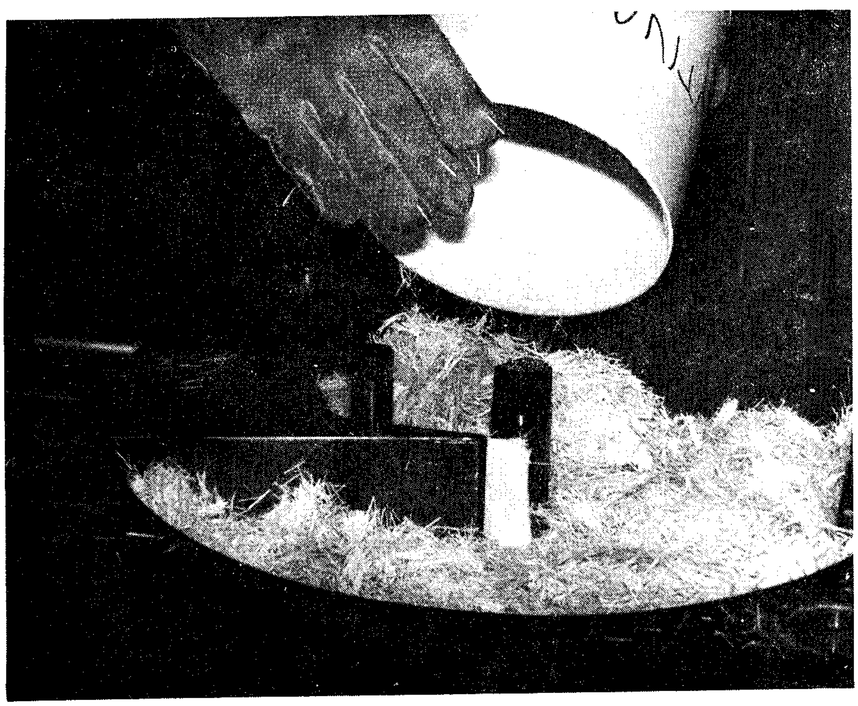


Figure 18. Bulk Molding Compound Being Loaded in Compression Mold for Quadrant Upper Disc.

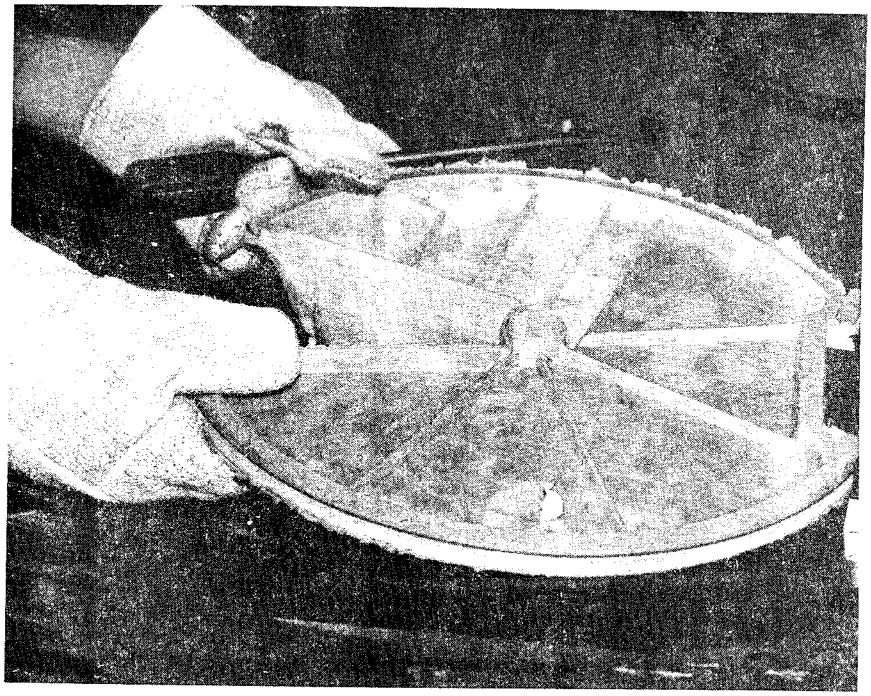


Figure 19. Upper Disc Being Removed From Mold.

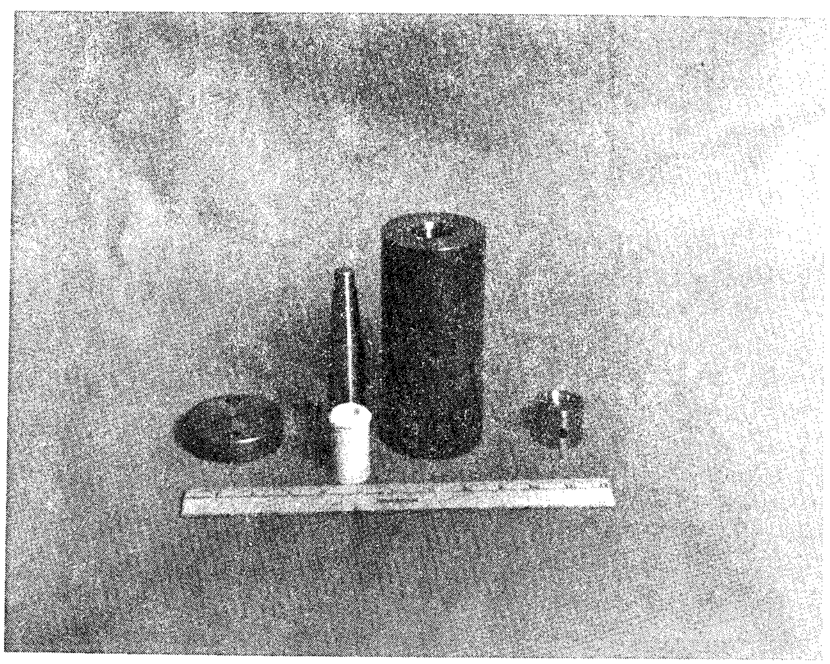


Figure 20. Matched Metal Compression Mold for Quadrant Insert.

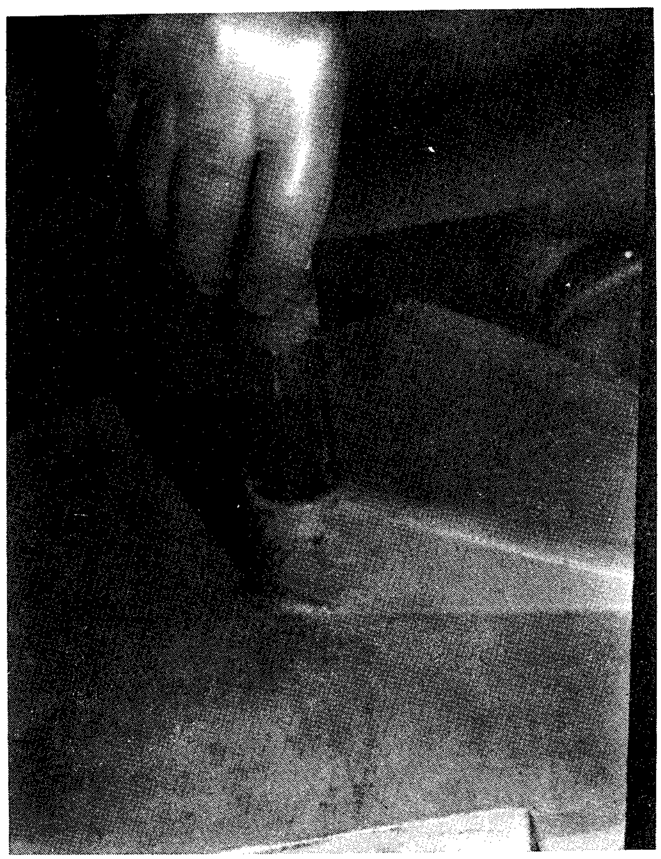


Figure 21. Installing Center Tube in Molded Quadrant Disc.

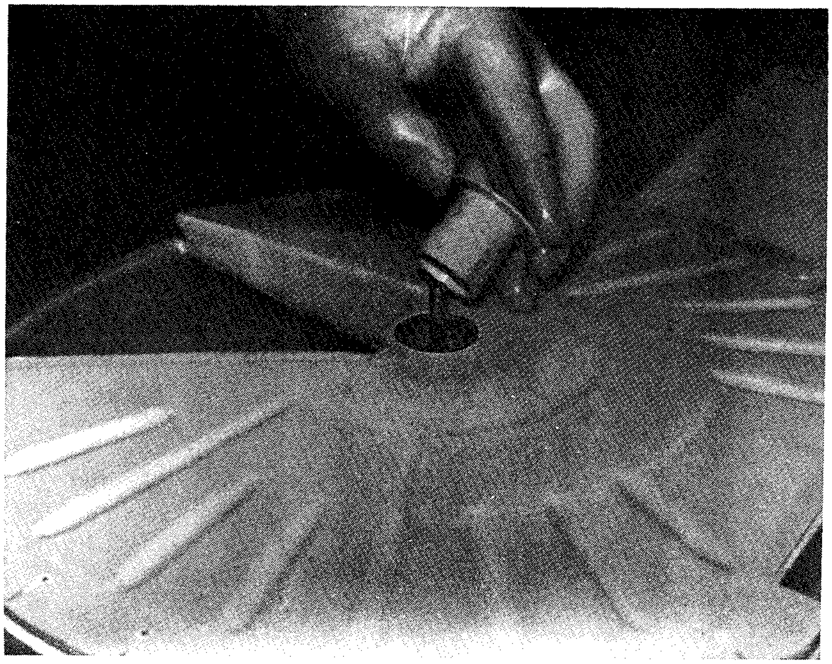


Figure 22. Installing Lower Insert in Quadrant.

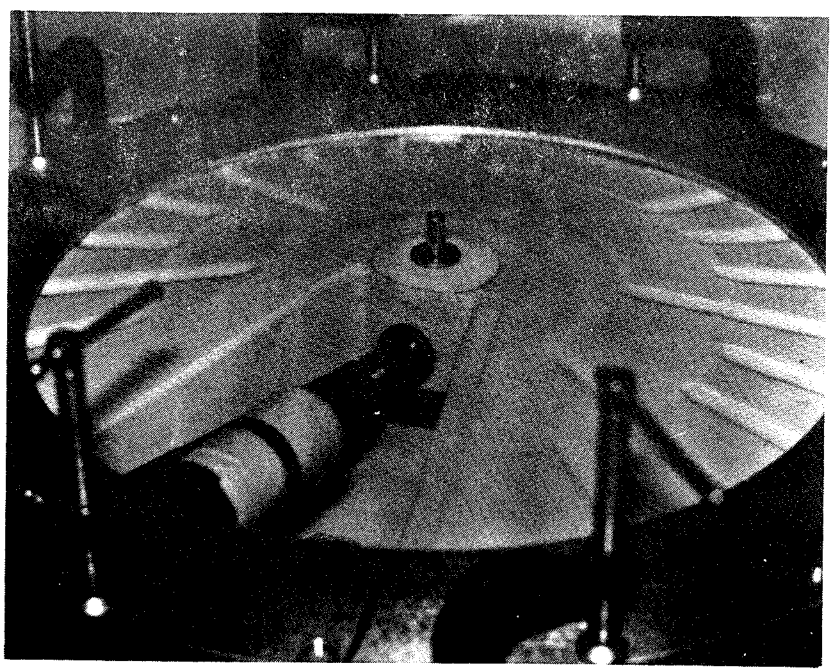


Figure 23. Assembly and Bonding Fixture for Quadrant.

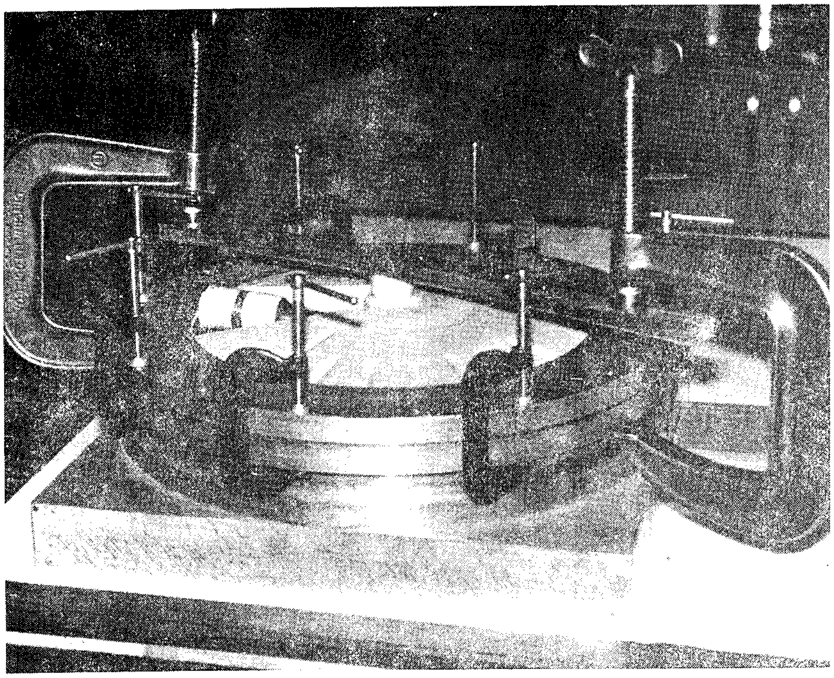


Figure 24. Assembly Fixture for Quadrant.

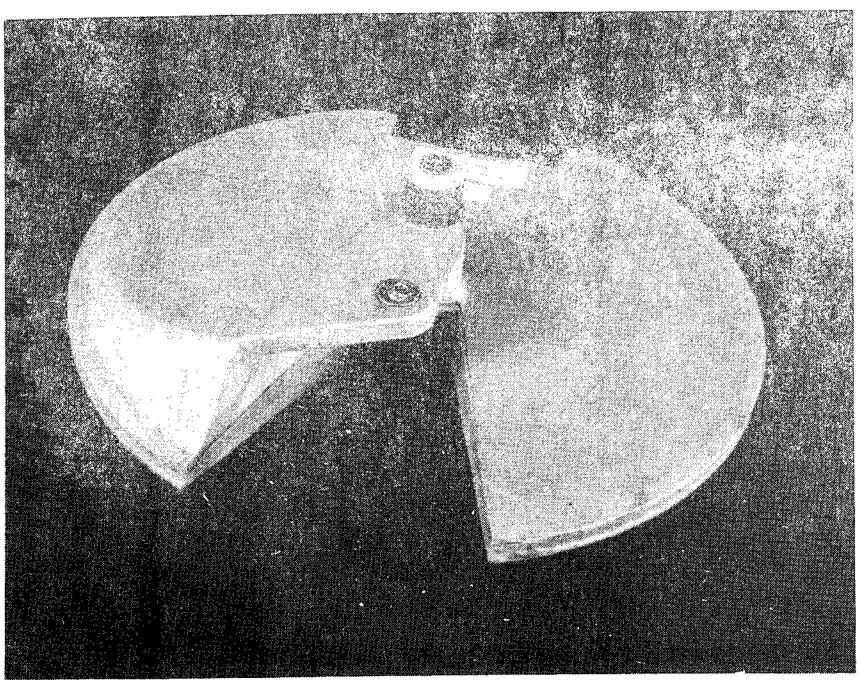


Figure 25. Quadrant Assembly.

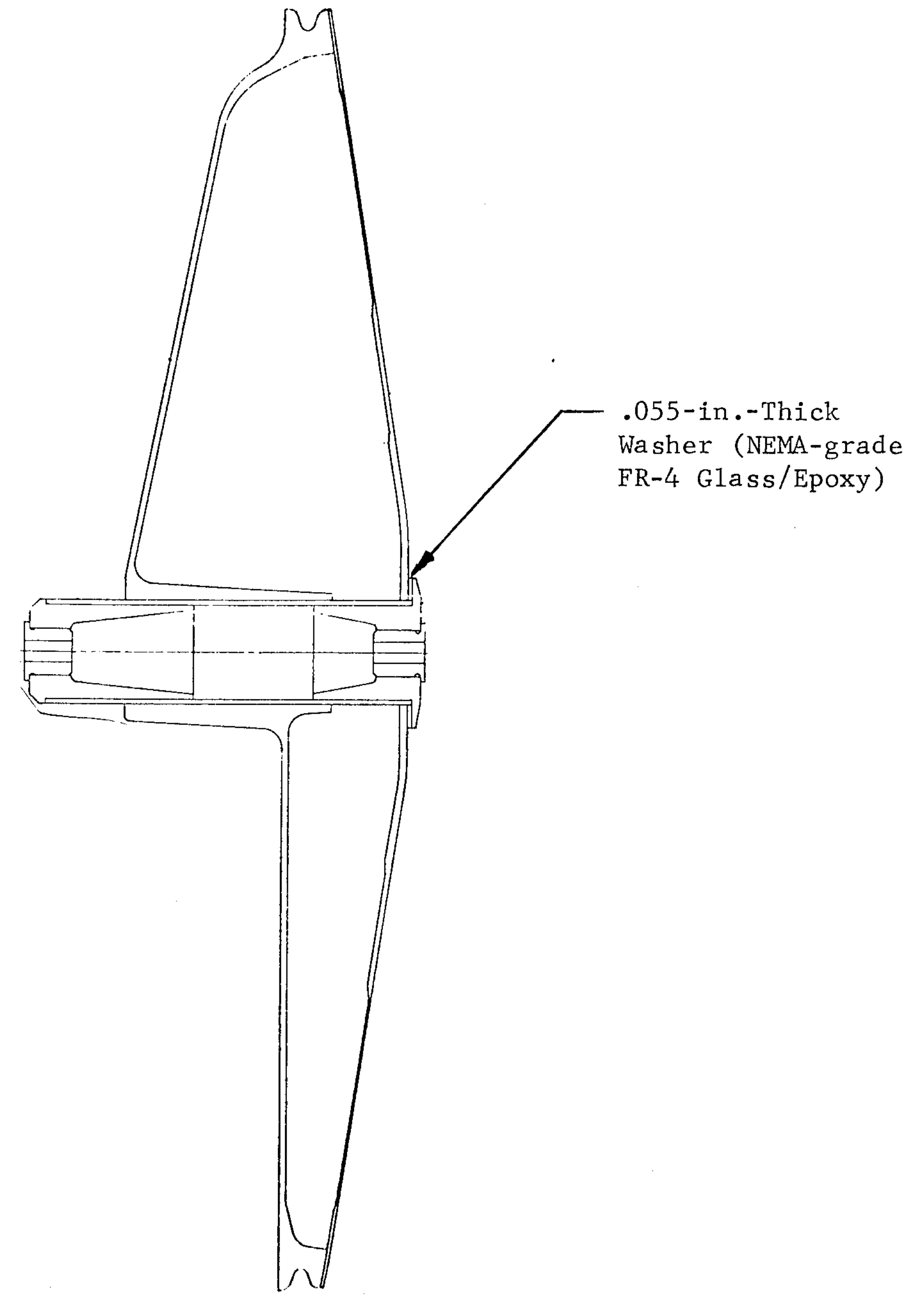



Figure 26. Modified Quadrant.

TABLE 4. VERIFICATION TEST PROGRAM

| Test No.→ / Set No. | 1 Fit & Function | 2 Fatigue | 3 Proof | 4 Ballistic | 5 Cyclic Loading | 6 Static Failure Load/Deflection | 7 High Temperature | 8 Temperature Shock | 9 Low Temperature | 10 Altitude | 11 Dust | 12 Humidity | 13 Fungus | 14 Salt Fog | 15 Vibration | 16 Sunshine | 17 Fuel & Oil Resistance | 18 Fire Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 C | | | | | 3 C | | | | | | | | | | 2 C | | |
| 2 | 1 C | | | | | 3 C | | | | | | | | | | | 2 C | |
| 3 | 1 C | | | | | 3 C | | | | | | | | | | | | 2 C |
| 4* | | | | 1 C | 2 C | 3 C | | | | | | | | | | | | |
| 5* | | | | 1 C | 2 C | 3 C | | | | | | | | | | | | |
| 6* | | 6 C C | | | | 7 C | 1 C | 2 C | 3 C | 4 C | | | 5 C | | | | | |
| 7 | | 4 C | | | | 5 C | | | | | 1 C | 2 C | | 3 C | | | | |
| 8 | | 2 C | | | | 3 C | | | | | | | | | 1 C | | | |
| 9 | S | P A R | E | | | | | | | | | | | | | | | |
| 10 | | 1 C C | 2 C C | | | | | | | | | | | | | | | |

NOTE: Number in Table is Order of Test.

C = Completed

* Quadrants of sets 4, 5, and 6 have also been tested for fit and function.

Shown below are the different agencies which conducted the verification testing.

| | |
|---|---|
| Eustis Directorate, USAAMRDL | Fit and Function |
| Approved Engineering Test Laboratories Chatsworth, California | Environmental: Altitude, Humidity, Sand and Dust, Fungus Resistance, Salt Spray, Ultraviolet Radiation; Structural: Vibration |
| General Dynamics/Convair San Diego, California | Ballistic |
| Whittaker Research and Development San Diego, California | Environmental: High Temperature Exposure, Temperature Shock, Low Temperature Exposure, Fuel and Oil Resistance, Fire Resistance; Structural: Static Loading, Fatigue and Load Cycling, Static Failure Load/Deflection. |

## Fit and Function Test

The first three sets of components that were fabricated during the manufacturing phase of the program were installed for operation aboard the UH-1 helicopter. The purpose of this test was to determine their ability to function correctly in the flight control system.

The results and findings of the fit and function tests are detailed below.

### Quadrant

When installing the quadrant in the UH-1 helicopter it was found that the center portion of the lower disc on the quadrant was rubbing against the heads of the three bolts that mount the lower bearing plate to the aircraft structure. A slight interference was also encountered between the lower surface of the rim containing the cable groove and a cable guard mounted on the aircraft structure.

To alleviate the interference problem, the next quadrants were assembled with the center tube, which contains the metallic bearing bushings, positioned 0.055 inch lower with respect to the molded upper disc. A 0.055-inch-thick washer made of NEMA-grade FR-4 epoxy/glass fiber laminate was placed between the flange of the lower insert and the lower disc. This arrangement had the effect of raising the disc portion of the quadrant 0.055 inch with respect to the lower bearing.

Three quadrants were assembled in this manner and installed in the helicopter. No interference or other problems were encountered. The remaining quadrants were then assembled with the above modifications. The modified quadrant is shown in Figure 26.

Connecting Link

No problems were encountered in the installation or functioning of the connecting link.

## Environmental Testing Results

Six sets of components were exposed to twelve different types of environmental tests. Table 4 shows the types of tests and the sequence in which they were performed. The following is a brief description of the tests which were conducted and the results which were obtained for each of the conditions.

### High-Temperature Test

The high-temperature exposure test was conducted on component set no. 6 in accordance with MIL-STD-810B, Method 501, Procedure I. The test consisted of installing the two components in a suitable chamber and raising the temperature in the chamber to +160°F. The temperature was maintained for 48 hours and the relative humidity was held at less than 15 percent. At the conclusion of the 48 hours, the temperature was returned to ambient and the components were removed from the chamber. A visual examination was conducted after the 48-hour exposure with the components still at 160°F and again after the components had reached room temperature. There was no evidence of damage to the parts.

### Temperature Shock

The temperature shock was conducted on component set no. 6 in accordance with MIL-STD-810B, Method 503, Procedure I. The components were placed in a test chamber and the temperature was raised to +160°F. The temperature in the chamber was maintained for 4 hours. At the conclusion of this time period the components were transferred within 5 minutes to a cold chamber with an internal temperature of -65°F. The components were exposed to this temperature for 4 hours, and then transferred within 5 minutes to the hot (+160°F) chamber. This cycle was repeated three times. After completion of the third cycle, the components were removed from the chamber and returned to room temperature. The components were visually inspected after the test. No degradation as a result of the test was noticed.

Low-Temperature Test

The low-temperature exposure test was also conducted on component set no. 6 in accordance with MIL-STD-810B, Method 502, Procedure I. The components were placed in a test chamber and the temperature was lowered to -65°F. The temperature was maintained for 72 hours. At the end of this time period the components were visually inspected. The parts were then allowed to return to room temperature and were again subjected to a visual inspection. There was no evidence of damage as a result of the test.

Altitude Test

The altitude test was conducted on component set no. 6 in accordance with MIL-STD-810B, Method 500, Procedure II. The components were placed in a suitable test chamber. The temperature was reduced to -65°F and the pressure was reduced to 3.44 in. of mercury, simulating an altitude of 50,000 ft. These conditions were maintained for 1 hour, after which the test chamber was returned to ambient conditions. At the conclusion of the test, the test articles were removed from the chamber and inspected. A visual inspection revealed no damage or adverse effects as a result of this test.

Sand and Dust Test

The sand and dust tests were conducted on component set no. 7 in accordance with MIL-STD-810B, Method 509, Procedure I. The components were installed in the test chamber in such a manner to allow sand and dust to circulate freely about the specimens. The specimens were subjected to a sand and dust density of 0.3±0.2 gram per cubic foot at a temperature of 73°F for a period of 6 hours. During this 6-hour period, the relative humidity was maintained at less than 20 percent and the air velocity was 1750±250 feet per minute.

The chamber temperature was then increased to 145°F and the sand and dust nozzles were turned off. These conditions were maintained for a period of 16 hours. During this 16-hour period, the relative humidity was maintained at less than 10 percent and the air velocity was 300±200 feet per minute.

With the chamber temperature maintained at 145°F, the sand and dust nozzles were turned on and a dust density of 0.3±0.2 gram per cubic foot was obtained in the test space. These conditions were maintained for a period of 6 hours. During the 6-hour period, the relative humidity was maintained at less than 10 percent, and the air velocity was 1750±250 feet per minute.

At the completion of the testing specified above, the specimens were removed from the chamber and were found to be lightly dusted. Visual examination revealed no degradation, deterioration, or other adverse effects.

## Humidity Test

The humidity test was conducted on set no. 7 in accordance with MIL-STD-810B, Method 507. The components were placed on polyethylene racks in the test chamber to allow circulation of air completely around the specimens. Within a period of 2 hours, the temperature was increased from room ambient to 71°C (160°F). The 71°C temperature was maintained for a period of 6 hours. During the following 16-hour period, the chamber temperature was gradually reduced to less than 35°C. This constituted one cycle. Ten cycles were performed.

Throughout the 240 hours of testing, the relative humidity was maintained at 95 percent minimum, and the water pH was 6.8. Visual examination at the completion of testing revealed no deterioration, damage, or other adverse effects.

## Fungus Resistance Test

The fungus resistance test was conducted on set no. 6 in accordance with MIL-STD-810B, Method 508, Procedure I. The components were sprayed with a suspension of viable fungus spores and then placed in a test chamber where an internal temperature of 85±1°F and a relative humidity of 96±1 percent were maintained. At the conclusion of the 28-day period, the components were removed from the chamber and were visually examined for presence of fungus growth. No fungus growth or other adverse effects were noticed.

## Salt Spray Exposure

The salt spray exposure test was conducted on component set no. 7 in accordance with MIL-STD-810B, Method 509. The components were installed in the test chamber and were subjected to a salt fog concentration of 5.0 percent for a period of 48 hours. During the 48-hour period, the temperature was maintained at 95°F, the salt solution pH was 6.9, the salt solution specific gravity was 1.032, and the salt spray fallout was 2.3 ml per hour per 80 square centimeters of horizontal collecting area.

At the completion of the 48-hour period, the components were removed from the chamber, were rinsed with distilled water, and were visually examined. No noticeable degradation or other adverse effects were noted.

## Ultraviolet Radiation Tests

The ultraviolet radiation (sunshine) tests were conducted on component set no. 1 in accordance with MIL-STD-810B, Method 505, Procedure I. The components were placed in a sunshine chamber. Thermocouples were placed as necessary. The chamber door was closed and

the lamps were turned on to radiate 100 to 120 watts per square foot upon the components. The chamber temperature was increased to 45°C (113°F). Following temperature stabilization, the conditions were maintained for a period of 48 hours. The chamber conditions were then returned to room ambient and the components were visually inspected.

Visual examination showed that the quadrant assembly had apparently faded from the original light green color to a yellow shade. There was no other evidence of damage as a result of the test.

Fuel and Oil Resistance Tests

Component set no. 2 was exposed to the fuel resistance test environment per Federal Test Standard 406, Method 7011. The test consisted of submerging the components for a period of seven consecutive days in each of three test fluids. The components were exposed first to a hydraulic fluid designated Aeroshell Fluid No. 4. The second exposure fluid was Brayco 932 Hydrocarbon Iso-Octane Fluid. The third and final fluid was Shell Aircraft Turbine Oil No. 307. After each 7-day test, the components were visually inspected and the weight change was recorded. No visual degradation as the result of the tests was detected. The weight change of each component is listed below.

After 7 Days in Aeroshell Fluid No. 4:

| Component | Weight Change |
|---|---|
| Quadrant | None |
| Link | None |

After 7 Days in Brayco 932 Hydrocarbon Iso-Octane:

| Component | Weight Change |
|---|---|
| Quadrant | +1.0 gm |
| Link | +1.0 gm |

After 7 Days in Aircraft Turbine Oil 307 (Shell):

| Component | Weight Change |
|---|---|
| Quadrant | +3.0 gm |
| Link | +7.0 gm |

Total Weight Change after 21 Days in the Various Fluids:

| Component | Weight Pre-Test | Weight Post-Test | Weight Change |
|---|---|---|---|
| Quadrant | 1476.0 gm | 1480.0 gm | +4.0 gm |
| Link | 992.0 gm | 1000.0 gm | +8.0 gm |

## Fire Resistance Test

The fire resistance test was conducted on component set no. 3 in accordance with directions by the Army Project Officer. The test was to simulate an on-board fire. The test fixture consisted of a 55-gallon drum, in which was placed a natural gas burner having a flaming area 6 in. wide and 12 in. long. The mixture of oxygen and natural gas was kept very rich to simulate a fuel fire. Each of the components was then lowered into the flames, exposing a critical area of the component. Thermocouple wires were placed on the component to indicate the heat rise that was obtained over a 2-minute exposure to the direct flames. During the test, observations were made to determine if the components ignited and, if they did, whether they would self-extinguish.

Connecting Link - The connecting link was suspended with one end approximately 8 in. above the burner and with its center line approximately 30° from the vertical plane. The outer tube ignited after 1 minute 15 seconds but self-extinguished when the component was raised. It was lowered immediately and after an additional 30 seconds the tube ignited again. The component was raised, but when the flames did not self-extinguish in 4 seconds, they were put out manually. The connecting link was lowered again. The tube ignited after 15 seconds but self-extinguished when the link was raised. The temperature at the time of the first ignition was 576°F and reached a peak of 654°F at the second ignition.

The molded end fittings showed only a slight degree of charring. The NEMA-grade G-11 FR-4 material in the outer tube was also charred slightly and showed evidence of delamination between the plies. The bonded joints appeared undamaged (Figure 27).

Quadrant - The quadrant was suspended in a horizontal plane with the lower disc approximately 8 in. above the burner. The lower disc ignited after 15 seconds but self-extinguished when the quadrant was raised. It was lowered immediately over the burner. The lower disc ignited after 20 seconds and did not self-extinguish when removed from the flames. The quadrant was again lowered but this time held approximately 18 in. above the burner. It was held in this position for the remainder of the 2 minutes (1 minute and 25 seconds). Towards the end of the test, the lower disc burned lightly but self-extinguished when removed from the burner. The temperatures reached were: 409°F and 497°F at the first two ignitions and 597°F at the end of the test.

The lower disc was severely charred and the surface was distorted in the area that ignited. The peripheral bond between the lower and upper discs had separated over a distance of 9 in. in the

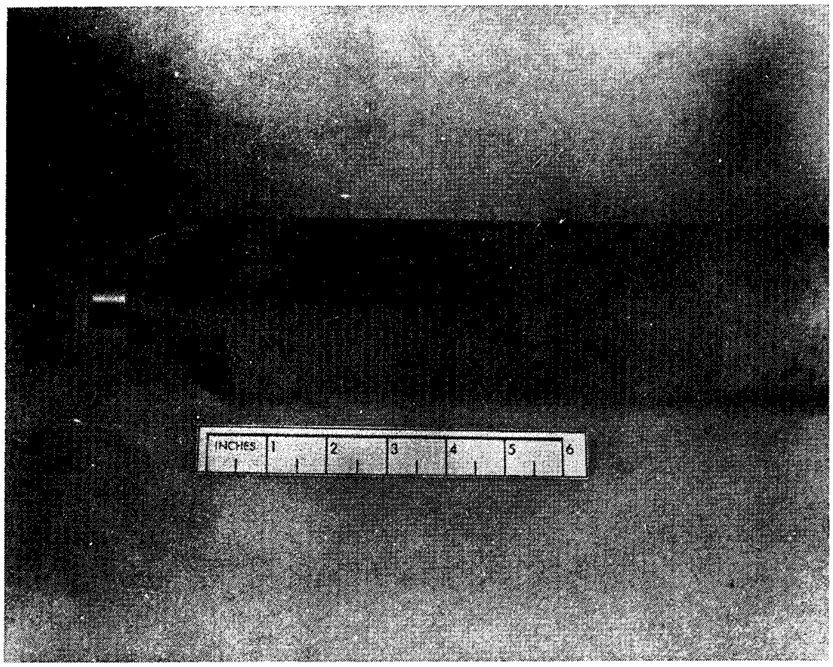



Figure 27. Connecting Link After Fire Test.

area where the cables are attached to the quadrant. The BMC material in the molded upper disc and fittings was only slightly discolored and did not appear to be damaged (Figure 28).

Due to the damage on the lower disc of the quadrant it was decided to apply a thermal protection coating to one of the earlier rejected lower quadrant discs and retest it separately for fire resistance. A 0.030-in.-thick coating (two coats) of 410-1A thermal protection coating was applied to the disc in accordance with NASA Tech Brief 70-10450. The coated lower quadrant disc was placed horizontally approximately 8 in. above the burner. After 1 minute and 45 seconds, it burned slightly, but the flames self-extinguished when the disc was raised approximately 12 in. The disc was immediately lowered again and held over the burner for 15 seconds to complete the 2-minute test. When removed, the disc was burning slightly, and when the flames did not self-extinguish after 5 seconds they were put out.

A visual examination revealed that the coating was completely charred and that the laminated material had not burned but had delaminated in some of the areas located between stiffener beads. The back surface of the disc was only moderately discolored.

## Structural Testing Results

After completion of the environmental tests, some of the components were subjected to fatigue cycling and proof loading. Component set no. 8, which had not been exposed to environmental testing, was subjected to vibration testing. The sequence of testing is shown in Table 4.

### Vibration Testing

Component set no. 8 was vibration tested in accordance with MIL-STD-810B, Method 514, Procedure I, Curve M.

Quadrant Assembly - The component was installed in a magnesium test fixture and was mounted on a vibration exciter as illustrated in Figure 29. The component was subjected to a search for resonance in each of the three major orthogonal axes over the frequency range of 5 to 500 to 5 Hz in a period of 15 minutes at the following intensities:

| Frequency (Hz) | Intensity |
|---|---|
| 5 - 20 | 0.10 in. da |
| 20 - 33 | 2.0 g peak |
| 33 - 52 | 0.036 in. da |
| 52 - 500 | 5.0 g peak |


Figure 28. Quadrant After Fire Test.

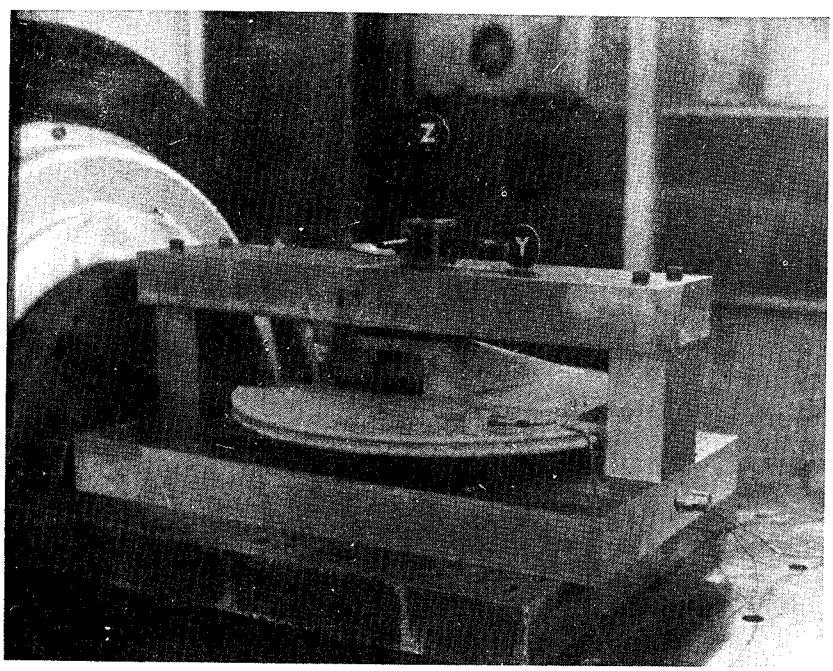



Figure 29. Vibration Test Setup for Quadrant.

During the search for resonance, the following resonances were noted:

| Axis | Frequency (Hz) |
|---|---|
| Z | 150 |
| X | 205 |
| | 388 |
| Y | 440 |
| | 380 |
| | 325 |
| | 195 |

The component was subjected to 30 minutes of resonance dwell in each of the resonance frequencies noted above. The component was then subjected to sinusoidal cycling over the frequency range of 5 to 500 to 5 Hz in 15-minute periods for total durations of 2 hours and 30 minutes in the Z axis, 2 hours in the X axis, and 1 hour in the Y axis. Visual examination at the completion of testing revealed no damage or other adverse effects.

Link Assembly - The component was installed in a magnesium test fixture and was mounted on a vibration exciter as illustrated in Figure 30. The component was subjected to a search for resonance at the frequencies and intensities described above. During the search for resonance, the following resonances were noted:

| Axis | Frequency (Hz) |
|---|---|
| Z | 230 |
| | 310 |
| | 495 |
| Y | 228 |
| | 320 |
| X | 385 |

The component was subjected to 30 minutes of resonance dwell at each of the resonances noted above. The component was then subjected to sinusoidal cycling over the frequency range of 5 to 500 to 5 Hz in 15-minute periods for total duration of 1 hour and 30 minutes in the Z axis, 2 hours in the Y axis, and 2.5 hours in the X axis. Visual examination at the completion of testing revealed no damage or other adverse effects.

During all vibration testing specified above, the outputs of the control and response accelerometers were recorded on an oscillograph.

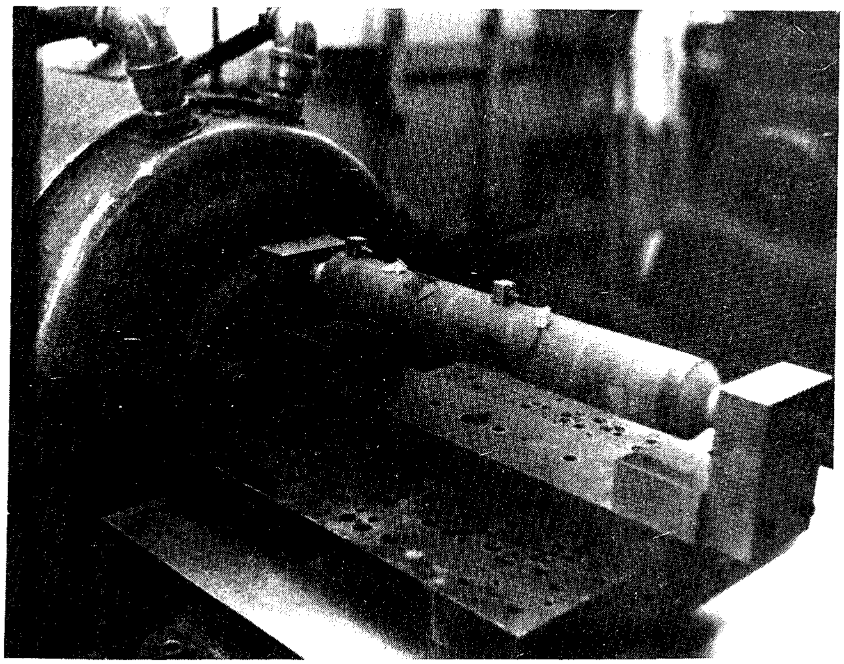


Figure 30. Vibration Test Setup for Connecting Link.

### Fatigue Testing

Fatigue testing was conducted on component sets 6, 7, 8, and 10. The components were installed in suitable fixtures which were mounted on the fatigue machine. Figures 31 through 34 show the test setup. The cyclic load was applied at a constant rate of 14.3 cps (860 cpm). One cycle consisted of a tension and compression load application of equal magnitude. The loads are listed in column B of Table 5.

TABLE 5. SUMMARY OF TEST LOADS

| Component | A<br>Proof Test (lb) ± 10 | B<br>Fatigue Test (lb) ± 10 | C<br>Static Preload for Ballistic Test (lb) ± 10 | D<br>Cyclic Load After Ballistic Test (lb) ± 10 |
|---|---|---|---|---|
| Connecting Link | 1017 (compression) | ±691 | 691 (compression) | ±691 |
| Quadrant | | | | |
| Cable | 530* | 70* | 353* | 70* |
| Lug | ±1325 | ±175 | ±883 | ±175 |

* Cable loads listed are those resulting from the loads applied at the lug. In addition, a preload of 50-100 lb was applied to each cable.

Deflection of the component was measured as shown by the location of the dial indicator in Figures 32 and 34 at the start of the fatigue test, after 2,500,000 load cycles and again after the completion of 5,000,000 cycles.

After the test, the components were visually examined. No damage was observed on any of the parts. No relaxation of the tightness of bearings and joints was noticed.

### Proof Load Testing

After completion of the fatigue test, component set no. 10 was subjected to proof load per column A of Table 5. Deflections were measured in the same manner as in the fatigue test. At the proof load the axial deflection of the connecting link was 0.007 in. The rotational deflection for the quadrant at proof load was 0.117 in. (lug in tension) and 0.089 in. (lug in compression). It should be

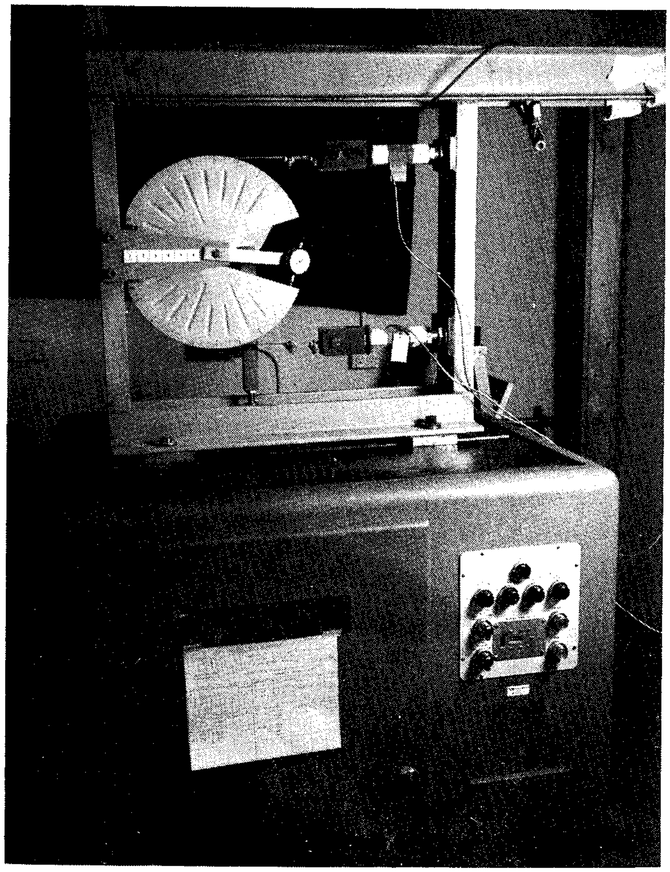
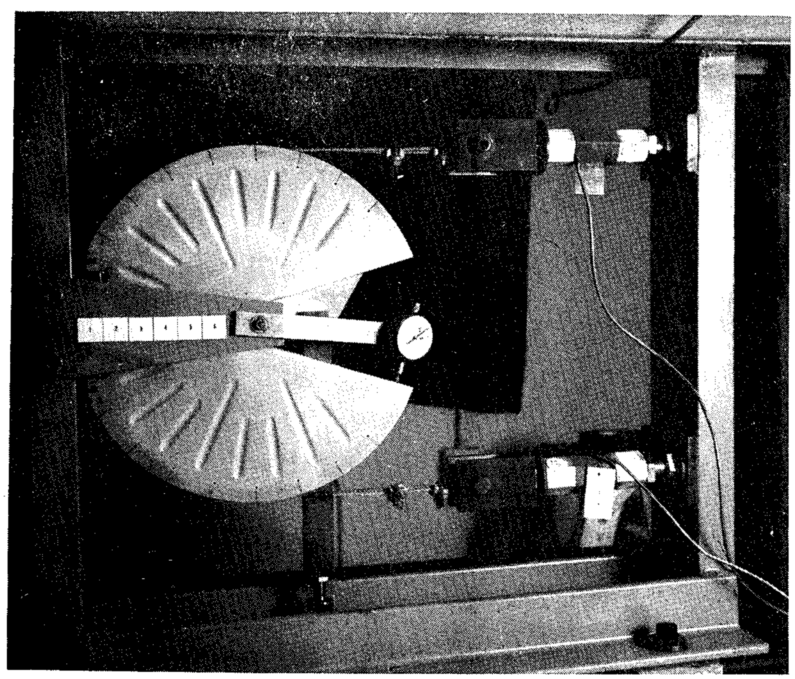


Figure 31. Fatigue Testing of Quadrant.

Figure 32. Deflection Measurement of Quadrant During Fatigue Test.



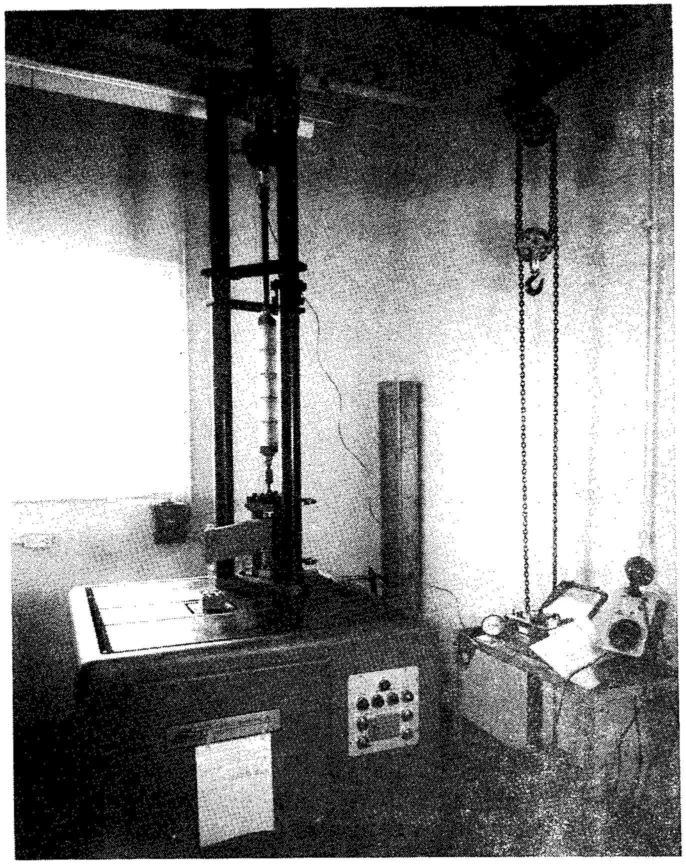


Figure 33. Fatigue Testing of Connecting Link.

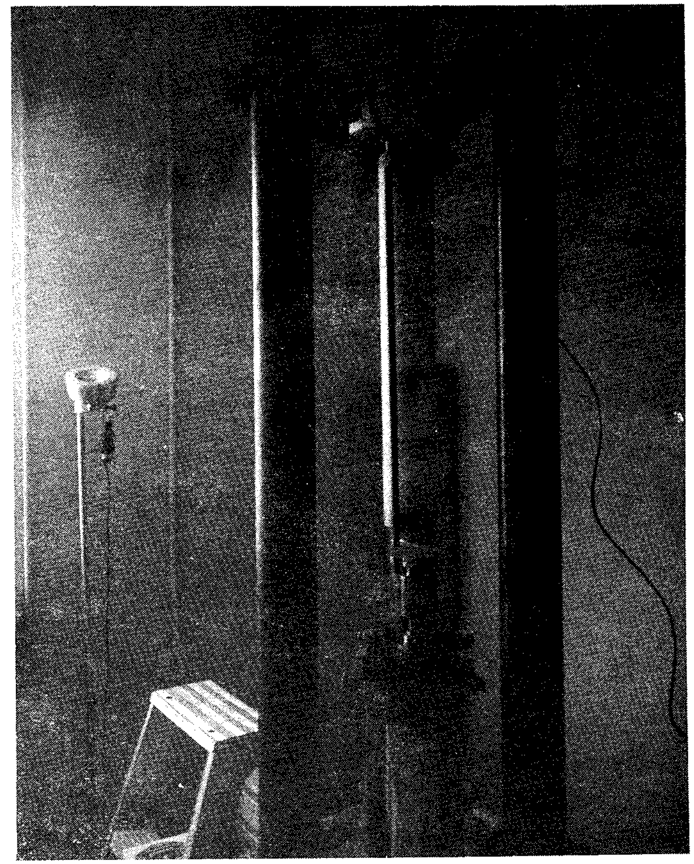


Figure 34. Deflection Measurement of Connecting Link During Fatigue Test.

recognized that this deflection also includes the elongation of the cables. The deflection within the part was not measured due to its complex shape. A visual inspection of the components after the completion of the proof load test did not reveal any damage or deterioration of any of the parts.

Cyclic Loading Testing

Component sets 4 and 5 were subjected to a cyclic loading test after the parts had undergone ballistic testing. The cyclic load test consisted of 2000 load cycles applied in the same manner as in the fatigue test described earlier. The loads were as shown in column B of Table 5, and the loading rate was 14.3 cycles per second. A visual inspection of the components at the completion of the test revealed no damage as a result of the test and no aggravation to the damage caused by the ballistic impact.

In addition to component sets 4 and 5, a connecting link with simulated ballistic damage was subjected to the cyclic load test. The simulated ballistic damage consisted of two 0.50-in.-wide by 1.5-in.-deep cuts which removed half of the cross-sectional area. The location of the cuts is shown in Figure 35. During the cyclic loading a side deflection due to the eccentric load path was noticed. The amplitude was estimated at approximately 0.05 in.

Ballistic Testing

Ballistic impact tests were conducted on component sets 4 and 5. The components were mounted in a fixture and loaded per column C of Table 5. The quadrant was loaded with the rod in compression. Deflections were measured during the load application. Deflections of the link assembly were measured between the two metallic end lugs, and the deflection of the quadrant assembly was measured perpendicular to a radius at a distance of 7.25 in. from the axis of rotation. An enclosure of polyethylene was built around the test fixture, and the temperature in the enclosure was raised to 160±5°F.

Component set no. 4 was impacted with fully tumbled .30 caliber AP projectiles at approximately 1800 fps velocity, and component set no. 5 was impacted with untumbled .50 caliber projectiles also at approximately 1800 fps velocity. Each component was impacted with one projectile. What was determined to be the most critical point in the component's load path was chosen as the point of ballistic impact. The location of the point of impact for both the .30 caliber and .50 caliber tests is shown in Figure 36 for the quadrant and in Figure 37 for the connecting link. The loads and deflections were recorded after impact. Table 6 is a summary of the test data.

Figures 38 and 39 show the test setup for the quadrant and Figure 40 shows the setup for the connecting link. Figures 41 through 47 show the damage inflicted by the impacting projectiles on the components.

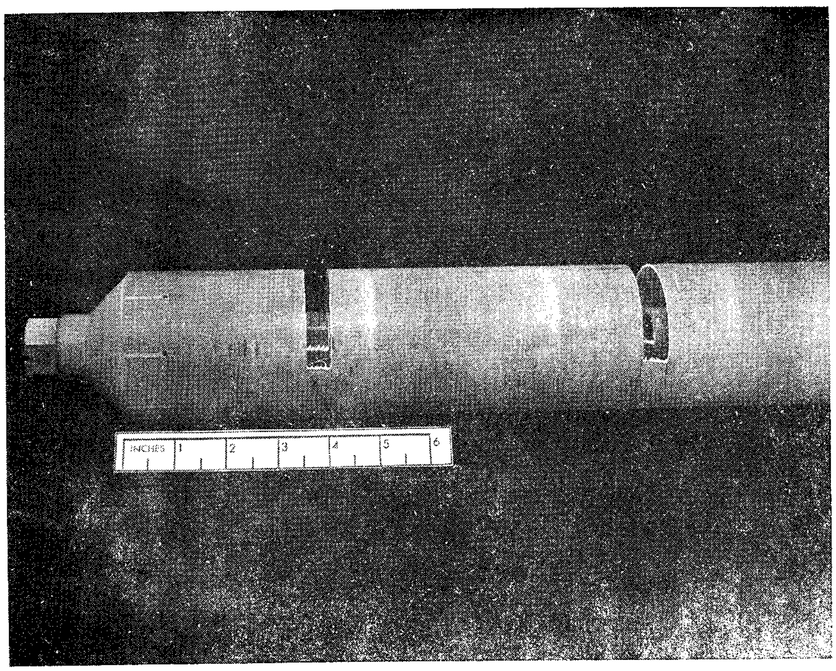



Figure 35. Connecting Link With Simulated
Ballistic Damage.

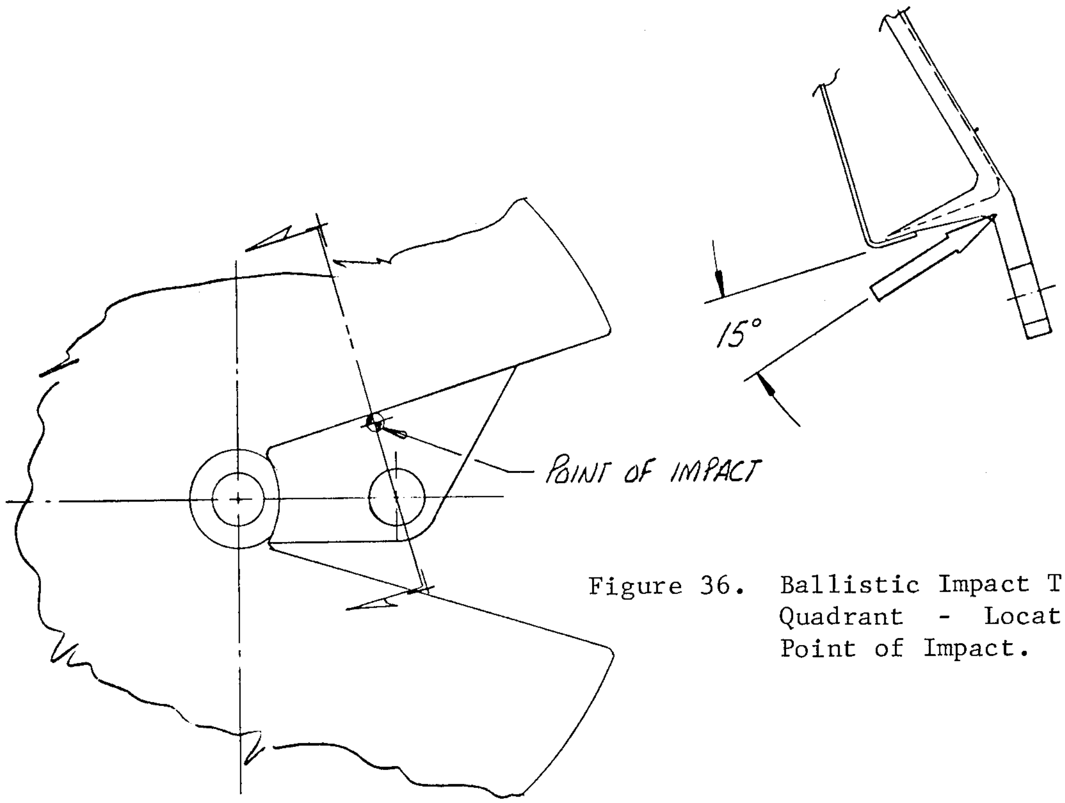



Figure 36. Ballistic Impact Test - Quadrant - Location of Point of Impact.

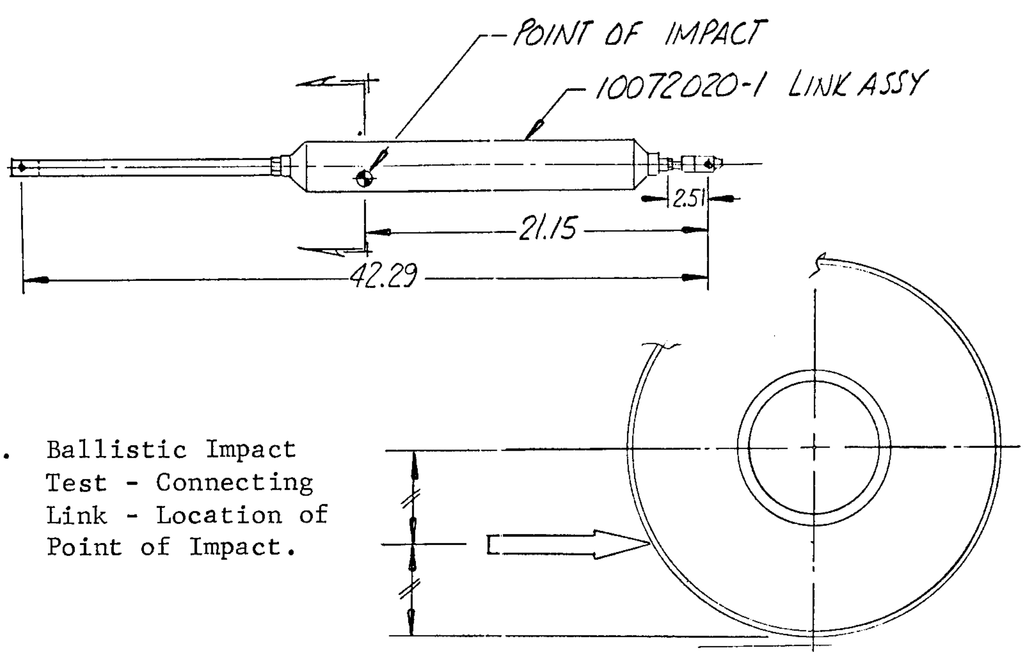



Figure 37. Ballistic Impact Test - Connecting Link - Location of Point of Impact.

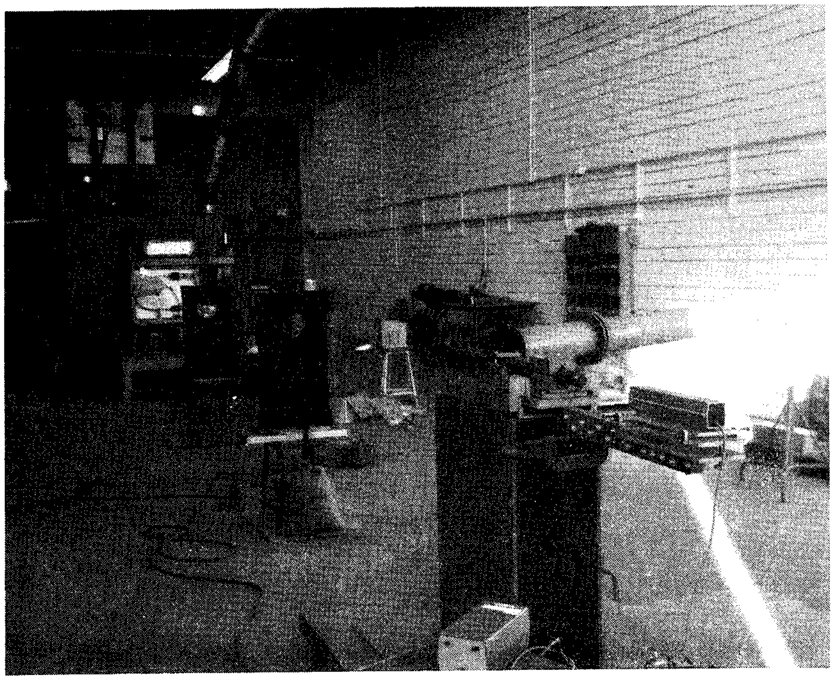


Figure 38. Firing Range.

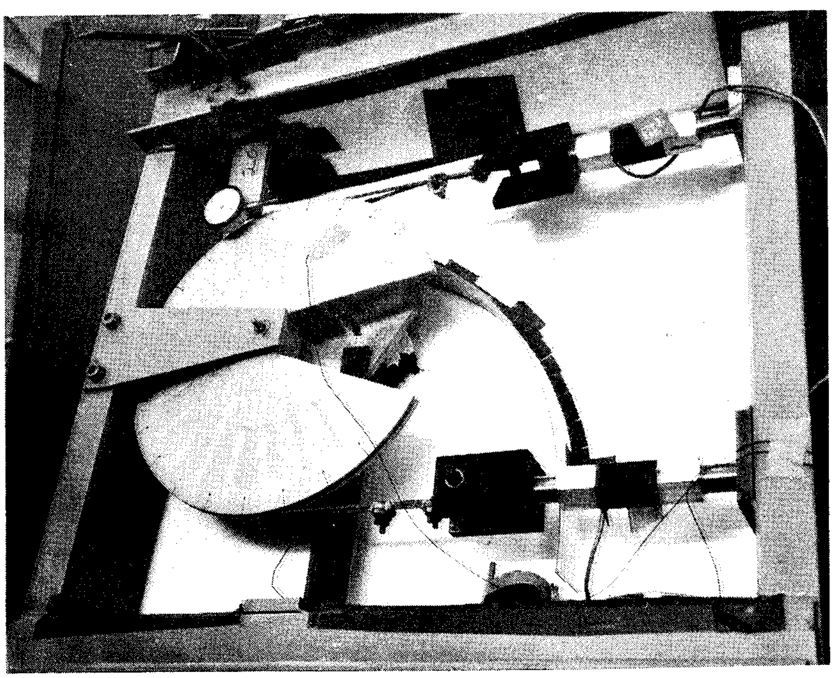


Figure 39. Ballistic Test Setup for Quadrant.

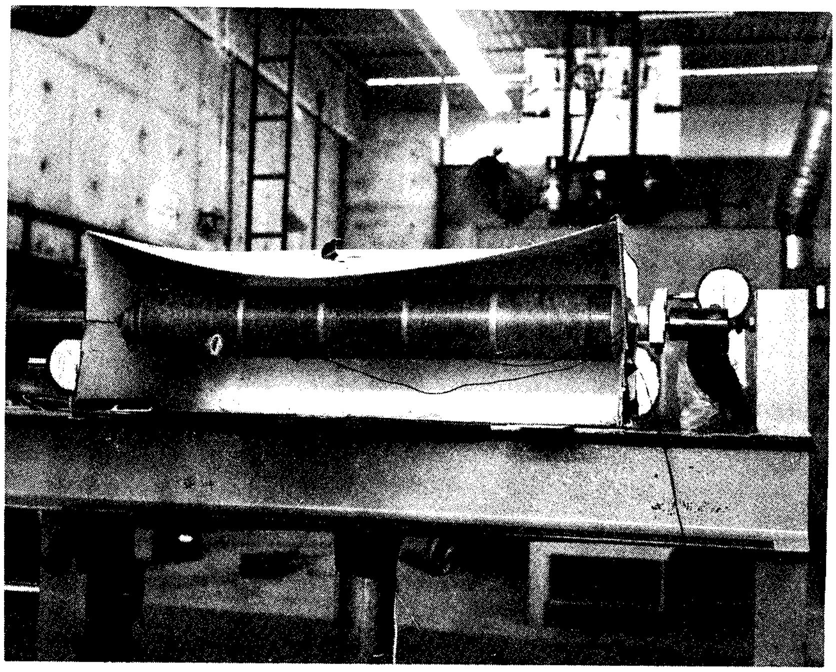


Figure 40. Ballistic Test Setup for Connecting Link.

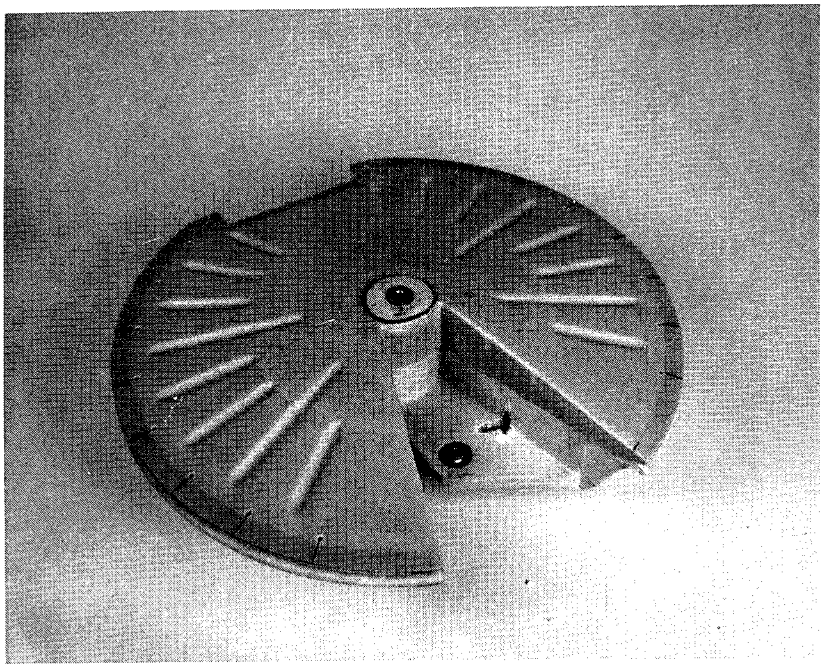


Figure 41. Quadrant After .30 Caliber Test - Impact Side.

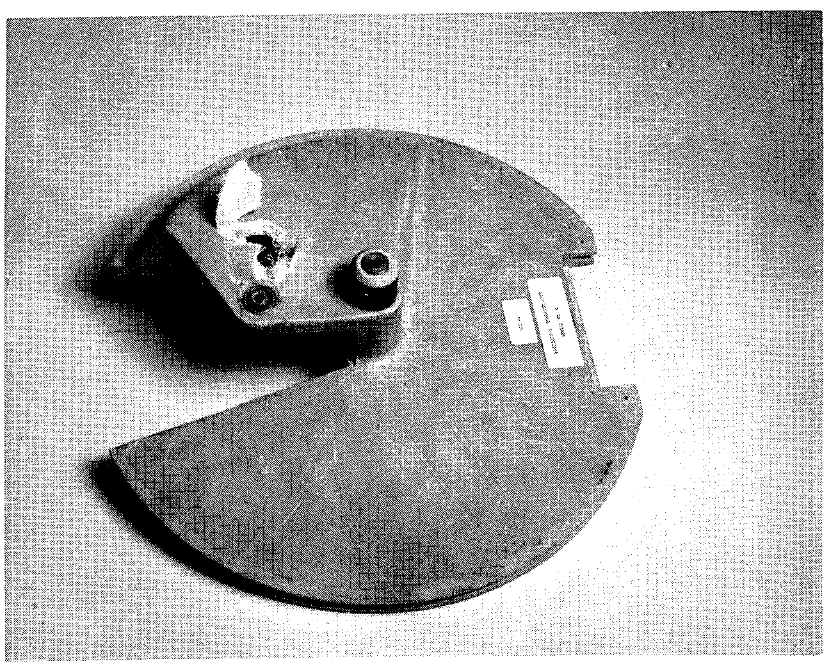


Figure 42. Quadrant After .30 Caliber Test - Exit Side.

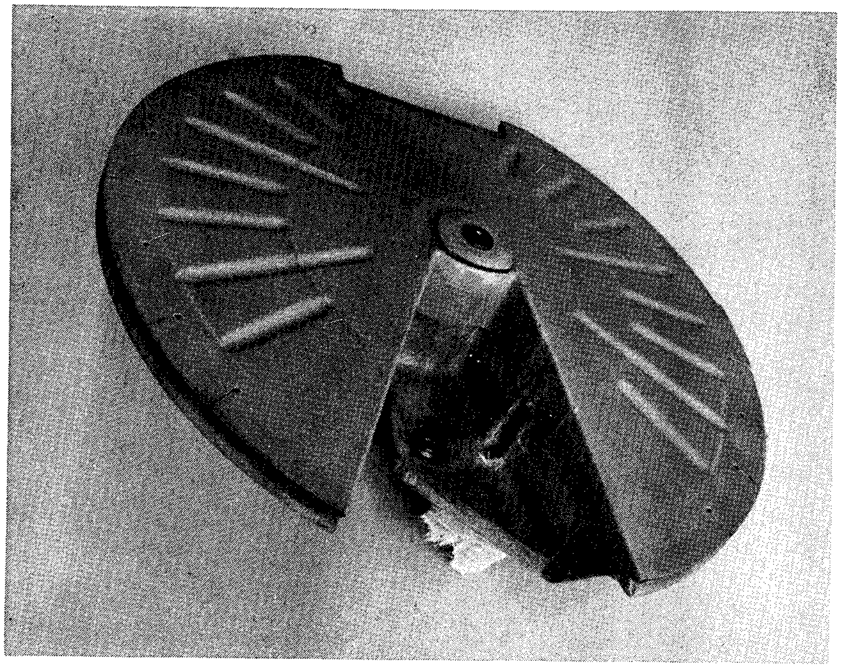


Figure 43. Quadrant After .50 Caliber Test - Impact Side.

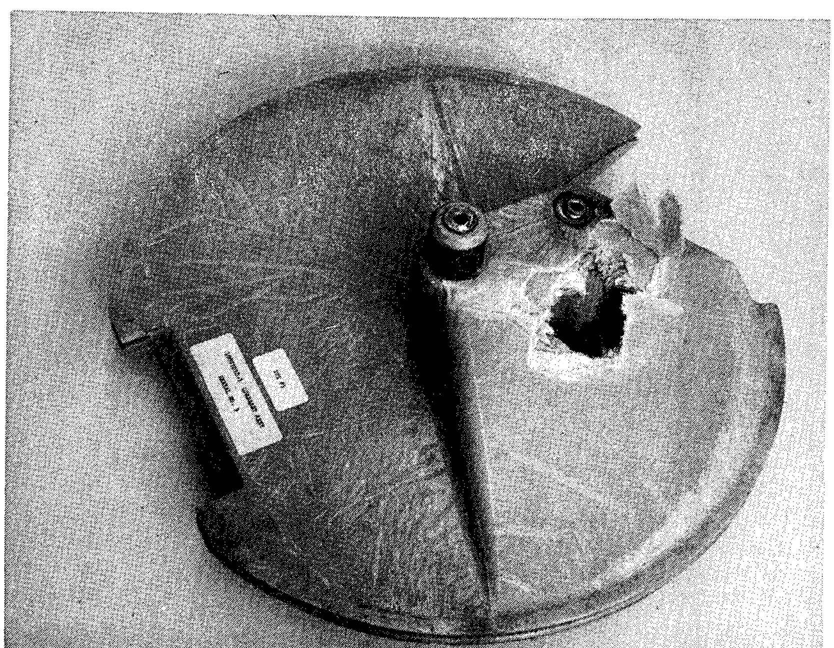


Figure 44. Quadrant After .50 Caliber Test - Exit Side.

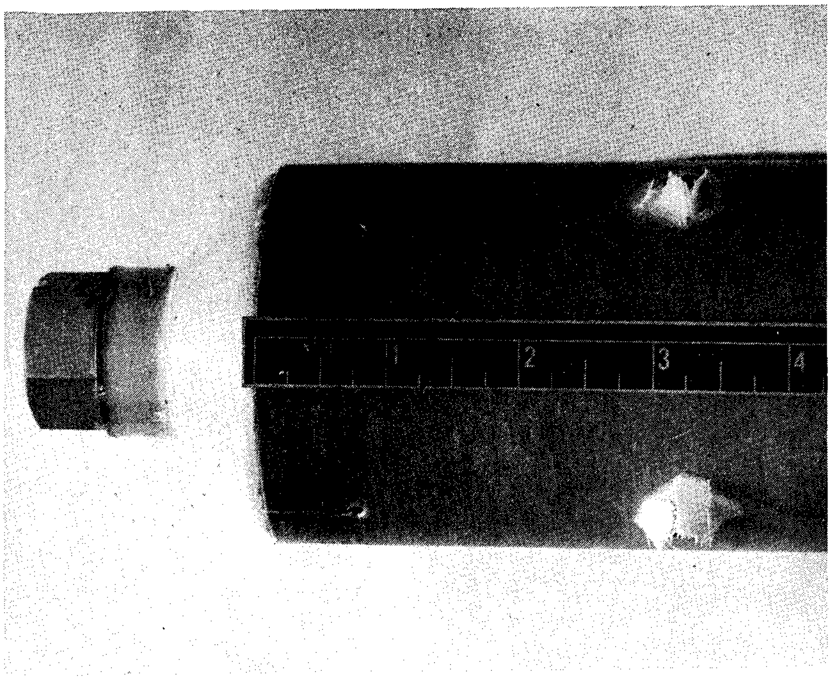



Figure 45. Connecting Link After .50 Caliber Test.

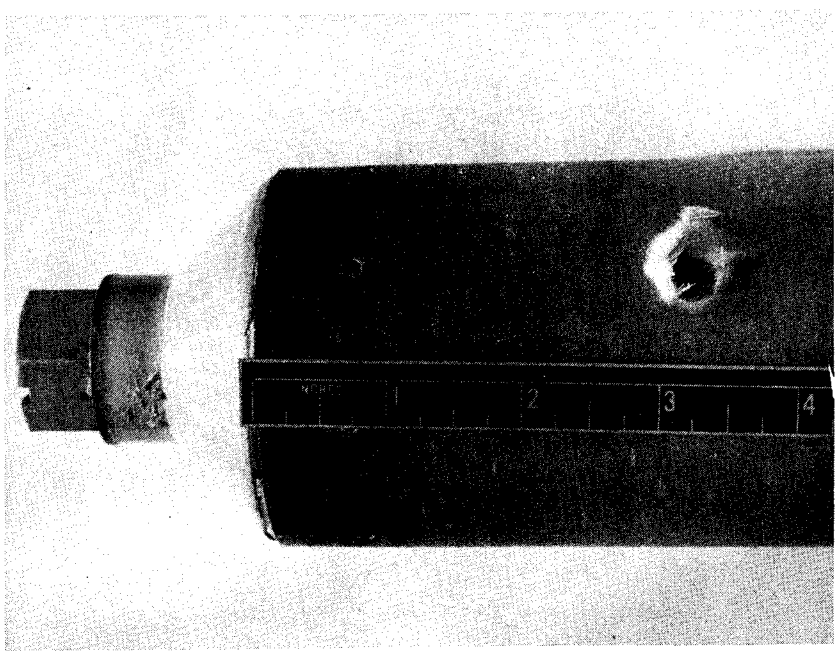



Figure 46. Connecting Link After .50 Caliber Test - Exit Side.

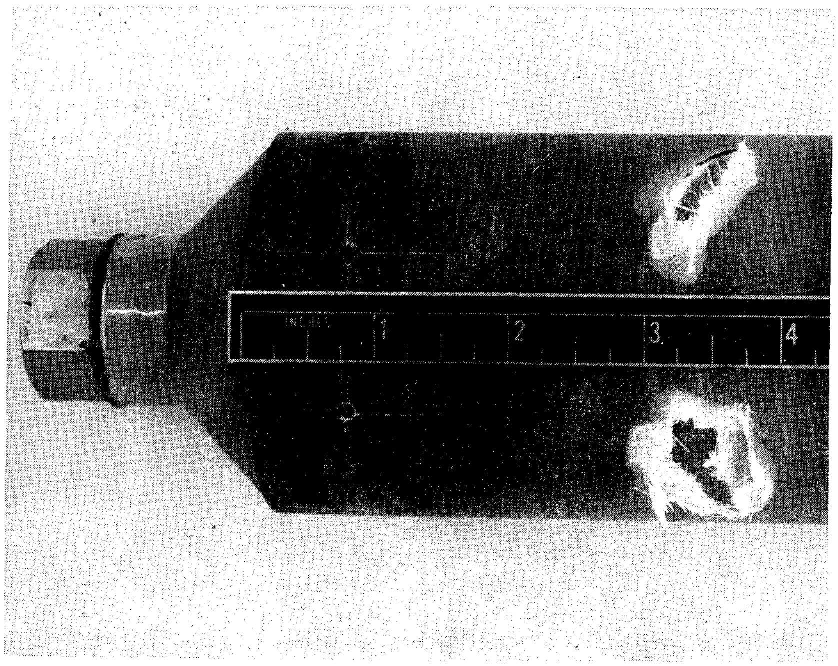



Figure 47. Connecting Link After .30 Caliber Test.

| TABLE 6. SUMMARY OF BALLISTIC IMPACT TESTS | | | |
|---|---|---|---|
| Component | Load (lb) | Deflection (in.) | Remarks |
| Set No. 4 | | | |
| Quadrant | 350 | .142 | Before impact |
| | 310 | .137 | After impact, .30 cal |
| Connecting Link | 690 | -.010 | Before impact |
| | 675 | -.011 | After impact, .30 cal |
| Set No. 5 | | | |
| Quadrant | 350 | .059 | Before impact |
| | 220 | no data* | After impact, .50 cal |
| Connecting Link | 690 | -.010 | Before impact |
| | 680 | -.010 | After impact, .50 cal |

* Indexing shoulder bonded to quadrant rim came off at impact.

The damage on the two connecting links was less than had been anticipated. In both the tumbled .30 caliber and the untumbled .50 caliber tests, some material remained intact in the outer tube between the openings made by the projectile. The inner tube was not damaged at all.

Because of the light damage on the link, it was decided to simulate a ballistic damage on another connecting link that had not been scheduled for the regular testing program. As was described above in the cycle test section, the simulated damage consisted of two cuts 0.50 in. wide by 1.5 in. deep through the side of the link. The cuts extended halfway through both the outer and inner tubes. The location and size of the cuts are shown in Figure 35.

## Static Failure Load/Deflection Testing

As the last step in the testing program, all component sets that had undergone the ballistic and environmental tests were subjected to ultimate loads to failure (see Table 5). During the load application, the deflections were continuously monitored and plotted against the load on an x-y recorder. The results of the tests are discussed below for each of the components.

### Quadrant

The quadrants of sets 4 and 5, which had been subjected to ballistic impact test, were loaded to failure with the rod in compression since it was assumed that due to the damage this would be the critical direction. The quadrant of set no. 4, which had been impacted with a tumbled .30 caliber projectile, failed at 2880 lb input load at the rod, or 217% of proof load, and that of set no. 5 (.50 caliber projectile) failed at 2550 lb input load at the rod, or 192% of proof load. Deflections at failure were .24 in. and .22 in., respectively. The deflection is measured perpendicular to a radius at a point 7-1/4 in. from the axis of rotation.

The test setup for the quadrant is shown in Figures 48 and 49. The dial indicator shown in the pictures is used only to calibrate the x-y recorder.

The two quadrants failed in the same manner, but not at the area damaged by the projectile as expected. Instead, the center tube tore out of the molded upper disc in the area of the lug. In order to establish the critical loading direction for the remaining quadrants, the components from sets 1 and 2 were loaded to failure with the rod in compression and tension, respectively.

The quadrant of set no. 1 failed at 2350 lb, or 177% of proof load, and the quadrant of set no. 2 failed at 1820 lb, or 137% of proof load. Based on these results it was decided to test the remaining quadrants in the same manner as set no. 2 with the rod in tension. A summary of the tests with description of failures is shown in Figure 50. It appears that the lower failure load of set no. 2 may be due to the fuel and oil test, which it was subjected to prior to the ultimate load test, rather than the direction in which it was tested. The summary in Figure 50 shows that with the exception of set no. 2 the failure loads are approximately the same for either loading direction. Figures 51, 52, and 53 show the different modes of failure of the quadrant.

### Connecting Link

The connecting link was mounted in the test fixture shown in Figure 54. The indicator dial was used only for calibrating the x-y recorder on which the deflection was recorded and monitored continuously throughout the test. The deflection was measured between the two metallic end fittings.

There were three different types of failures. Connecting links from sets 1, 6, and 8 failed when the bond between the outer tube and the upper fitting sheared, and subsequently split the outer tube. The links with ballistic impact damage failed in compression in the damaged area, and the link that had been subjected to the fire

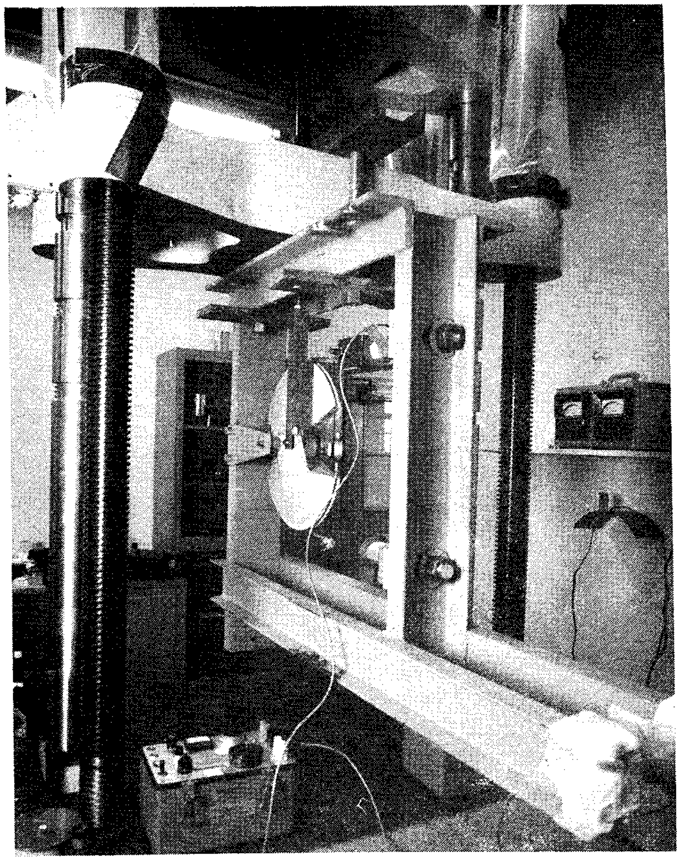


Figure 48. Static Failure Load Test of Quadrant. Lug Loaded in Tension.

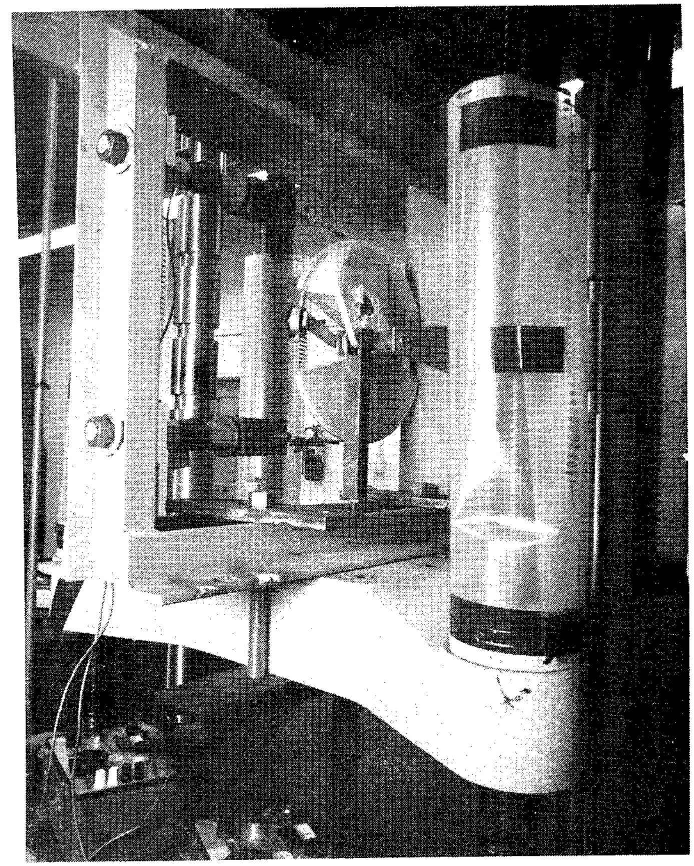
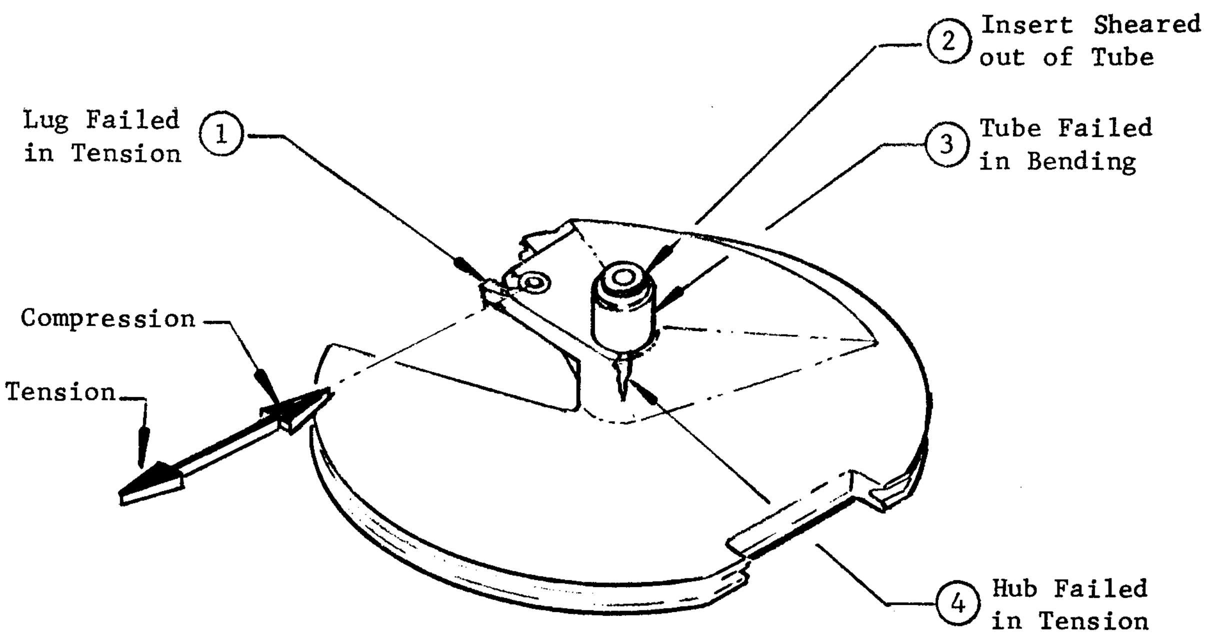


Figure 49. Static Failure Load Test of Quadrant. Lug Loaded in Compression.




| Set | Type Load | Failure Load (lb) | % of Proof Load | Deflection at Failure Load* (in.) | Type of Failure | |
|---|---|---|---|---|---|---|
| 1 | Compression | 2350 | 177 | .17 | 3 | - |
| 2 | Tension | 1820 | 137 | .15 | 1 | Fig. 51 |
| 3 | Tension | 2680 | 202 | .23 | 1 | Fig. 51 |
| 4 | Compression | 2880 | 217 | .24 | 4 | Fig. 52 |
| 5 | Compression | 2550 | 192 | .22 | 4 | Fig. 52 |
| 6 | Tension | 2600 | 196 | .17 | 1 | Fig. 51 |
| 7 | Tension | 2980 | 225 | .20 | 3 | - |
| 8 | Tension | 3120 | 235 | .20 | 2 | Fig. 53 |

*Deflection measured perpendicular to a radius 7-1/4 in. from axis of rotation.

Figure 50. Summary of Static Failure/Deflection Tests of Quadrant.

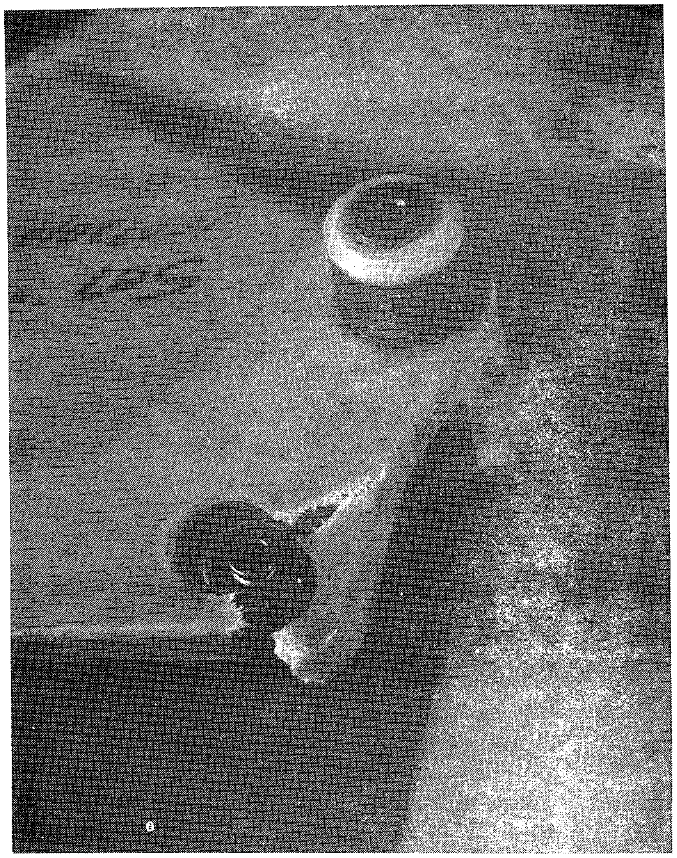


Figure 51. Static Failure Load Test - Quadrant - Lug Tension Failure.

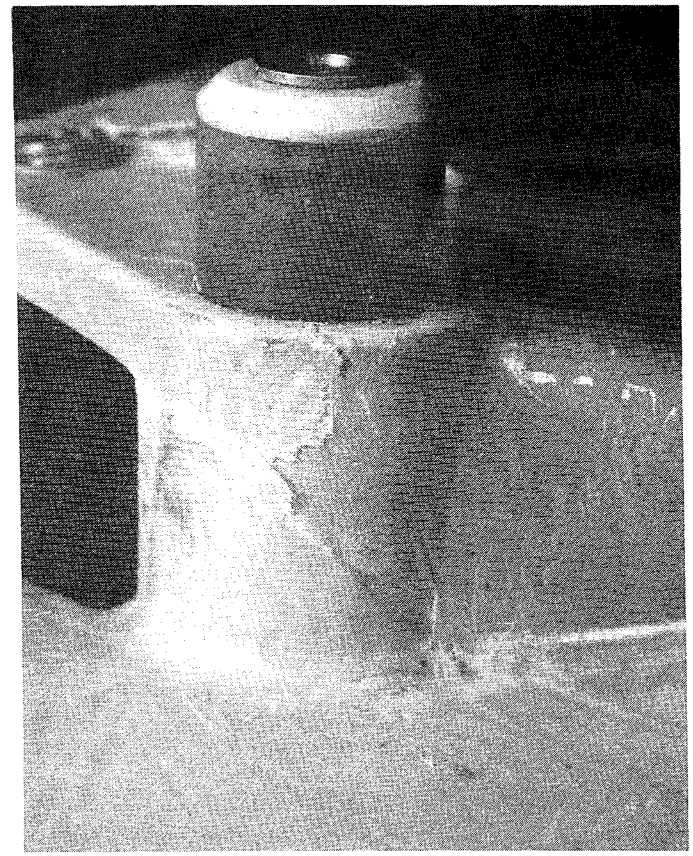


Figure 52. Static Failure Load Test - Quadrant - Hub Tension Failure.

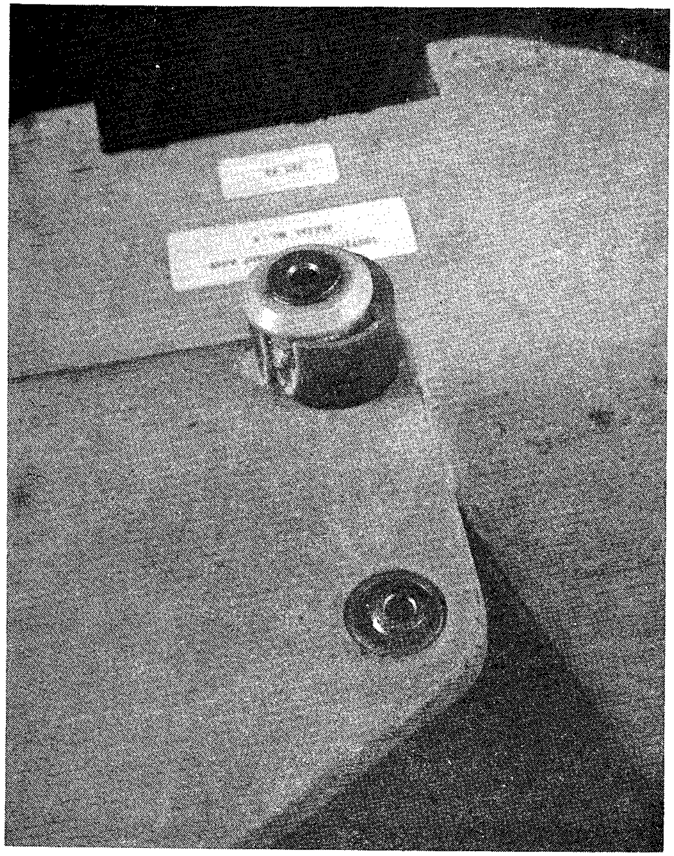


Figure 53. Static Failure Load Test - Quadrant - Upper Insert Tear-Out.

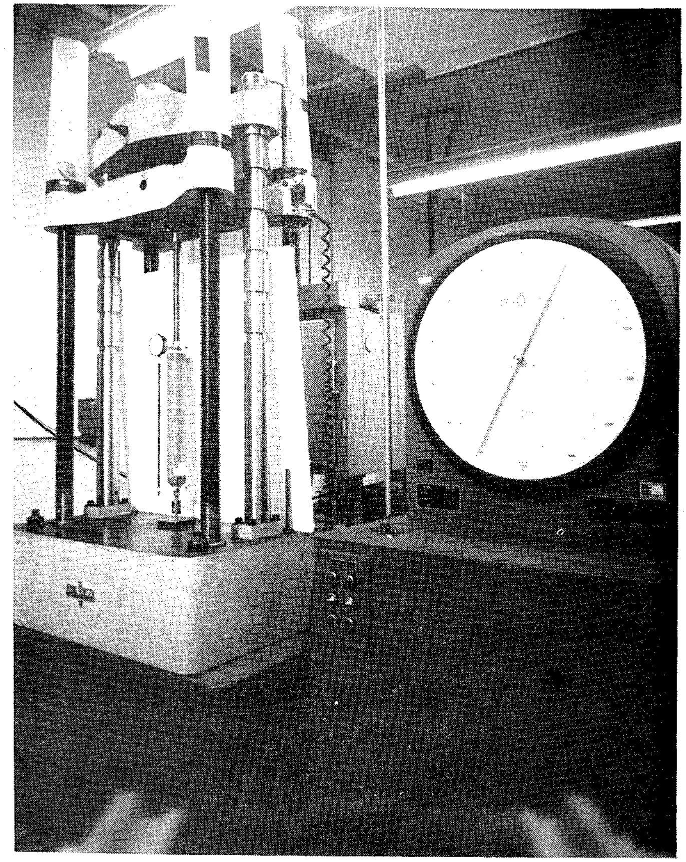


Figure 54. Static Failure Load Test of Connecting Link.

resistance test failed in compression of the outer tube in the burned area. Two connecting links did not fail. The lower rod end failed in bending for set no. 2, and set no. 7 deflected laterally and the test was stopped when the load did not increase and the load/deflection curve flattened out. The tests are summarized in Table 7.

TABLE 7. SUMMARY OF STATIC FAILURE/DEFLECTION TESTS OF CONNECTING LINK

| | Yield | | Failure | | | |
|---|---|---|---|---|---|---|
| Set | Defl. (in.) | Load (lb) | Defl. (in.) | Load (lb) | % of Proof Load | Type of Failure |
| 1 | .066 | 7400 | .079 | 8320 | 818 | Bond failure. Fig. 55. |
| 2 | .082 | 6600 | .086 | 6920 | 680 | Rod end failure. |
| 3 | .065 | 6550 | .084 | 6700 | 659 | Compression failure. Fig. 56. |
| 4 | - | - | .046 | 4300 | 423 | Compression failure. Fig. 57. |
| 5 | .052 | 5000 | .059 | 5540 | 545 | Compression failure. Fig. 57. |
| 6 | .066 | 7400 | .076 | 7520 | 739 | Bond failure. Fig. 55. |
| 7 | .048 | 5200 | .086 | 6760 | 665 | Bent, did not fail. |
| 8 | .057 | 5800 | .082 | 6450 | 634 | Bond failure. Fig. 55. |
| 11* | .028 | 1000 | .050 | 1380 | 136 | Bending failure. Fig. 58. |

* Simulated ballistic damage.

The different types of failure of the connecting link are shown in Figures 55 through 58.

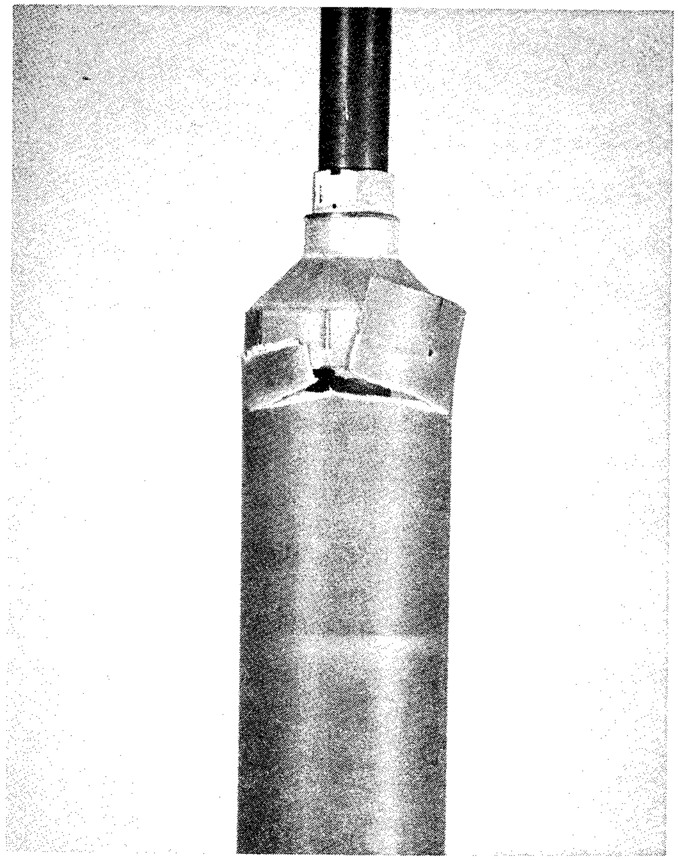


Figure 55. Shear Failure of Bond Between Outer Tube and End Fitting. Typical for Sets 1, 6, and 8.

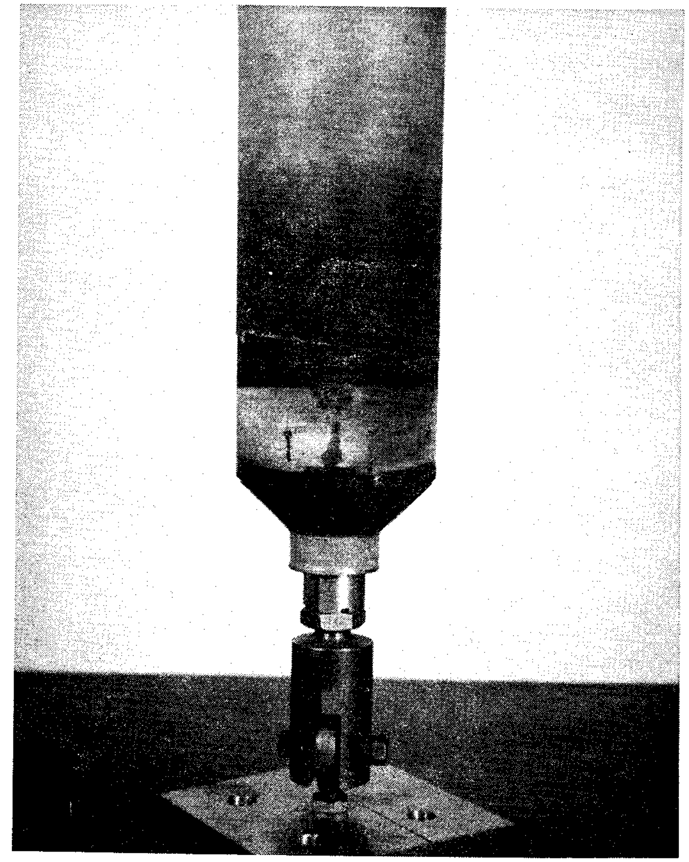


Figure 56. Outer Tube Failed in Compression in Burned Area. Set No. 3.

Figure 57. Outer Tube Failed in Compression in Area Damaged by Ballistic Impact. Sets 4 and 5.

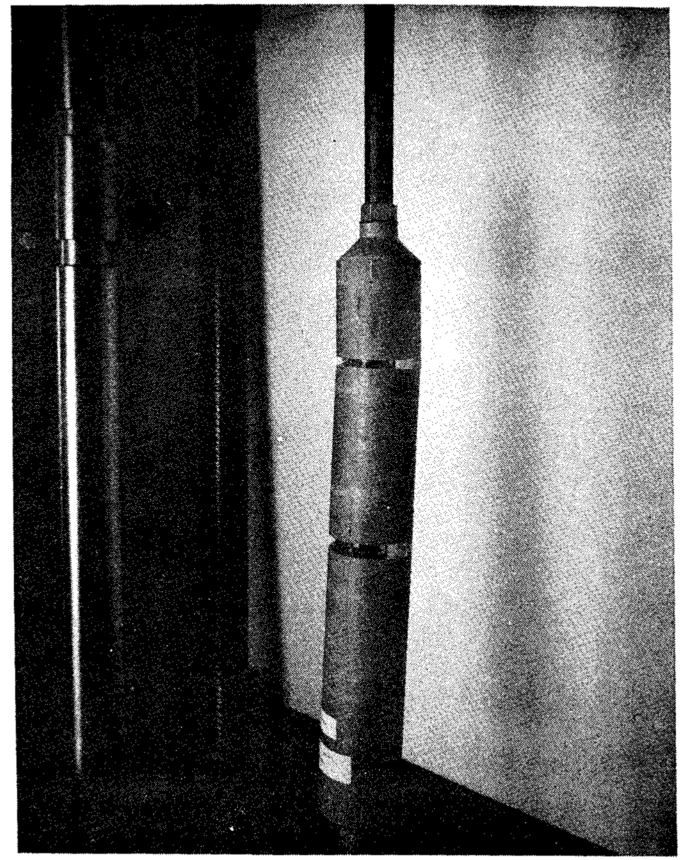


Figure 58. Failed Connecting Link With Simulated Ballistic Damage.

## CONCLUSIONS

The results and findings of this program permit the following conclusions regarding the design, fabrication, and performance of ballistic tolerant flight control components fabricated from fiber glass reinforced plastics.

1. The design of the two components is greatly simplified compared to the previous design of these components from composite materials.

2. The manufacturability of the component assemblies is greatly simplified compared to previous manufacturing methods.

3. The matched-die molding of the epoxy bulk molding compound with the complex details of the components proved to be a cost effective and highly reliable method of producing these elements.

4. The hybrid matched-metal-die molding concept proved to be an effective and efficient means of incorporating continuous glass reinforcement in a part with complex geometry.

5. The use of assembly fixtures to locate and bond the individual details of each component proved not only to be cost effective but was an in-process method of inspecting each of the details prior to installation and inspection of the final cured and assembled component.

6. A more simplified manufacturing method and materials concept would be the fabrication of all details made from the epoxy bulk molding compound in lieu of the hybrid concept which incorporates continuous glass reinforcement.

7. The high failure loads on components with ballistic damage indicate that they may be somewhat overdesigned. Further ballistic testing with the point of impact located in various critical areas would indicate where weight savings could be realized.

## RECOMMENDATIONS

Based on the results and conclusions of this program, it is recommended that:

1. The washer that was placed under the flange of the lower fitting on the quadrant, as a result of problems encountered in the fit and function test, be replaced by a corresponding thicker flange on the molded fitting.

2. A more fire-retardant resin in the laminated quadrant lower disc or a thermal protection coating be applied to the outside surface of the lower disc to improve the fire resistance of the quadrant assembly.

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